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AEOLUS

Algorithmic Principles for Building Efficient Overlay Computers

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Algorithmic solutions and services for resource management and QoS

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1 Introduction

The major aim of the AEOLUS Sub-Project 5 is that of extending global computing to users connected by heterogeneous mobile/dynamic ad-hoc networks.

According to the declared *objectives*, our annual research activity has focused on the following issues.

- Studying different wireless network models that well simulate the heterogeneous scenarios where global computing functionalities use to work on. This task has been carried out from both analytical and experimental points of view.
- Providing dynamic-resource and role-assignment strategies that guarantee some connectivity properties of the wireless network and, at the same time, the node energy consumption is minimized.
- Designing communication protocols for mobile ad hoc networks in presence of unpredictable and non-homogeneous faults.

A major novelty of our approach is that Issues 2 and 3 have been also considered together as a *multi-criteria* optimization problem that considers several levels of the network architecture.

We remind (see also the previous Deliverables of WP 5.1) that our approach departs significantly from standard theoretical research in ad hoc networks. This is due to the aim of implementing some particular functionalities over wireless heterogeneous systems arising in the context of *Global Computing*. The main features of the issues studied in this WP concerns both *(i)* the adopted network model and *(ii)* the particular adopted techniques for the design and the analysis of the proposed algorithmic solutions.

As for the first issue, the major novelty of our research lies in considering networks having *non-uniform* node fault probability. Furthermore, we consider self-organized, heterogeneous sensor networks where different roles and functionalities are assigned to nodes according to their physical wireless connectivity and sensing characteristics. We indeed identify the need of organizing a wireless/sensor networks according to the tasks appropriate for each sensor node based on their initial deployment in the network.

As for the second issue, the global computing applications require the design of efficient communication protocols which are very flexible and easy to implement in order to be adapted and applied in hybrid networks where nodes may have different technology and energy power. For this reason, rather than designing very complex and involved protocols, we focus our attention on the performance analysis of simple fully-distributed protocols based on simple techniques such as the greedy and divide-et-impera ones.

2 Modelling heterogeneous wireless networks

2.1 Sensor networks as random intersection graphs

The *uniform random intersection graphs model* $G_{n,m,\lambda}$ was first introduced by Godehardt and Jaworski in [27]. In this model, to each of the n vertices of the graph, a random subset of λ elements of a universal set of m elements in total is independently assigned. Two vertices u, v are then adjacent in the $G_{n,m,\lambda}$ graph if and only if their assigned sets of elements have at least one element in common. This model is closely related to random intersection graphs $G_{n,m,p}$ (introduced by Karoński, Sheinerman and Singer-Cohen [30] and Singer-Cohen [43]), in which each one of m labels is chosen independently with probability p by each one of n vertices, and there are edges between any vertices with overlaps in the labels chosen. The $G_{n,m,\lambda}$ seems to behave similarly to $G_{n,m,p}$ when one can show concentration on the number of labels chosen by a vertex in the latter (which can happen for quite large λ). However, notice that for small values of λ such concentration results do not hold, and the statistical behavior of the two models is quite different.

Importance and motivation. Random intersection graphs may be used to model several real-life applications characterized by local interactions quite accurately (compared to the $G_{n,\hat{p}}$ model where edges appear independently with probability \hat{p}). In particular, the $G_{n,\hat{p}}$ model is inappropriate for describing some real world networks (like sensor and social networks) because it lacks certain features of those networks, such as a scale free degree distribution and the emergence of local clusters. One of the underlying reasons for this mismatch is its independence of the edges, in other words the missing transitivity that characterizes such networks: if vertices x and y exhibit a relationship of some kind in a real world network and so do vertices y and z , then this suggests a connection between vertices x and z , too.

For example, we consider the following scenario concerning efficient and secure communication in sensor networks: The vertices in our model correspond to sensor devices that blindly choose a limited number of resources among a globally available set of shared resources (such as communication channels, encryption keys etc). Whenever two sensors select at least one resource in common (e.g. a common communication channel, a common encryption key), a communication link is implicitly established (represented by a graph edge); this gives rise to communication graphs that look like random intersection graphs. Particularly for security purposes, the random selection of elements in our graphs can be seen as a way to establish local common keys on-line, without any global scheme for predistribution of keys. In such a case, the set of labels can be a global set of large primes (known to all) but each node selects uniformly at random only a few. Two nodes that have selected a common prime can communicate securely. Notice that no other node can know what numbers a different node has selected. Thus, the local communication is guaranteed to be secure.

Random intersection graphs in general and in particular the uniform random inter-

section graphs model $G_{n,m,\lambda}$ are relevant to and capture quite nicely social networking. Indeed, a social network is a social structure made of nodes (individuals or organizations) tied by one or more specific types of interdependency, such as values, visions, financial exchange, friends, conflicts, web links etc. Social network analysis views social relationships in terms of nodes and ties. Nodes are the individual actors within the networks and ties are the relationships between the actors.

Other applications may include oblivious resource sharing in a distributed setting, interactions of mobile agents traversing the web etc. In fact there are practical situations where each communication agent (e.g. a wireless node) gets access only to some ports (statistically) out of a possible set of communication ports. When another agent also selects a communication port, then a communication link is implicitly established and this gives rise to communication graphs that look like random intersection graphs. Even epidemiological phenomena (like spread of disease) tend to be more accurately captured by those “interaction-sensitive” random graph models.

Related works. Uniform random intersection graphs were first considered by Godehardt and Jaworski in [27], where they focused on the distribution of the number of isolated vertices in $G_{n,m,\lambda}$, as well as the distribution of vertex degrees. The vertex degree distribution of general random intersection graphs (where the choice of the label sets S_v is made according to a general distribution) was studied independently by Blonzelis [5] and Deijfen and Kets [22]. Connectivity and communication security aspects of $G_{n,m,\lambda}$ in various important settings is studied in [23, 4].

The question of how close $G_{n,m,p}$ and $G_{n,p}$ are for various values of m, p has been studied by Fill, Sheinerman and Singer-Cohen in [25]. In [38], the authors investigate expansion properties of $G_{n,m,p}$ and give tight bounds on the mixing and the cover time of random walks on instances of the random intersection graphs model. Algorithms for finding large independent sets in $G_{n,m,p}$ were proposed in [37, 39] (however, no attempt was made to see how close the independent sets given by those algorithms are to optimal size). The authors of [24] find thresholds (that are optimal up to a constant factor) for the appearance of hamilton cycles in random intersection graphs. The efficient construction of hamilton cycles in $G_{n,m,p}$ is studied in [41]. Also, by using a sieve method, Stark [44] gives exact formulae for the degree distribution of an arbitrary fixed vertex of $G_{n,m,p}$ for a quite wide range of the parameters of the model.

Our contribution. As proved in [25], the spaces $G_{n,m,p}$ and $G_{n,\hat{p}}$ are equivalent when $m = n^\alpha$, with $\alpha > 6$, in the sense that their total variation distance tends to 0 as n goes to ∞ . Also, the authors in [41] show that, when $\alpha > 1$, for any monotone increasing property there is a direct relation (including a multiplicative constant) of the corresponding thresholds of the property in the two spaces. Finally, as noted before, the models $G_{n,m,p}$ and $G_{n,m,\lambda}$ seem to have similar statistical behavior when we can show concentration of mp around λ , which happens especially when $m = \omega(n)$ and for p large enough. Hence, it

is very important to investigate what is happening when $m = n^\alpha$, with $\alpha \leq 1$ and λ not too large compared to m , where the uniform random intersection graphs model seems to differ the most from both $G_{n,m,p}$ and $G_{n,\hat{p}}$.

The main focus of our work [40] is about hamiltonicity and independent sets in the uniform random intersection graphs model $G_{n,m,\lambda}$, for the regime $\alpha < 1$. In particular:

- (a) We show that when the number of vertices n is at least $(1 + \epsilon) \binom{m}{\lambda} \ln \binom{m}{\lambda}$, for some constant $\epsilon > 0$ as small as possible, then $G_{n,m,\lambda}$, with $\lambda \geq 2$, has a Hamilton cycle with high probability (whp), i.e. a very small constant number of labels suffices to yield hamiltonicity. The proof uses the coupon collector's problem together with an interesting combinatorial construction.
- (b) By using a far from trivial application of the first and second moment methods, we show that when $m = n^\alpha$ for some fixed constant $\alpha < 1$ and for all $\lambda = O(m^{1/4})$, the independence number of the $G_{n,m,\lambda}$ model is approximately $\frac{m}{c_0\lambda}$, where c_0 is the smallest real number that satisfies $c_0 \geq 1$ and

$$c_0^{-1} \left(\frac{1}{\alpha} - 1 \right) \frac{\ln m}{\lambda} = c_0^{-1} + (1 - c_0^{-1}) \ln(1 - c_0^{-1}) - \frac{\ln(c_0\lambda)}{c_0\lambda}.$$

- (c) Finally we give a note on $G_{n,m,p}$, that provides bounds on its independence number. Note that this was left open in [37, 39].

2.2 A mobility simulation tool

In [9] we describe the MOMOSE tool, which is a highly flexible and easily extensible environment for the simulation of mobility models. Indeed, MOMOSE not only allows a programmer to easily integrate a new mobility model into the set of models already included in its distribution, but it also allows the user to let the nodes of the MANET move in different ways by associating any mobility model to any subset of the nodes themselves. This is especially relevant in our setting, since the devices constituting an overlay computer are different from each other, and it is even more unrealistic than in traditional settings to assume the same mobility assumptions to be valid for all the network nodes.

Within the MOMOSE framework a programmer can easily implement new mobility models and successively simulate the movement of a set of nodes by using any combination of the mobility models included in the MOMOSE distribution and of the newly implemented mobility models. During each simulation, the set of the nodes of the networks is partitioned into an arbitrary number of subsets, each one corresponding to the specific mobility model governing the movement of the nodes in the subset: however, since each node has its own logic unit which is independent from the other nodes, different nodes in the same subset are allowed to play different roles within the same mobility model (for example, in the PursueModel it is necessary to allow one node to act as the leader of the subset).

MOMOSE also allows the user to simulate the movement of the nodes within a *realistic environment*, where obstacles (such as buildings and barriers) are present: these obstacles not only limit the movement of the nodes, but they also attenuate the transmission signals sent by the communication units. The definition of a scenario is flexible enough to allow the user to define significantly different situations, ranging from people moving within a building or a campus to robots moving within a disaster recovery environment or to vehicles moving within an urban environment (such as in a VANET).

During a simulation, one or more data recorders can be used, which allows the user to collect the interesting data that could be used to produce statistics or reports. The current distribution of MOMOSE includes a data recorder that produces trace files compatible with the NS-2 network simulation environment, which is one of the most popular network simulator within the research community. As far as we know, the mobility modules produced for this simulator include only very simple mobility models: MOMOSE can hence be used in order to produce more realistic mobility patterns, which can be subsequently used by NS-2 while simulating and evaluating any network protocol.

It thus follows that the impact of this new framework for mobility models in the analysis of QoS and resource management in heterogeneous wireless networks (i.e. the subject of WP 5.1) is very important: It allows us to validate protocols and negative (i.e. impossibility) results over realistic wireless network models arising from Global Computing scenarios. Previous standard network simulators are not suitable for this task.

2.3 Role assignment for heterogeneous wireless networks

One of the main goals of the analysis of a social network consists of determining patterns of relationships and interactions among social actors (such as persons and groups) in order to identify the social structure of the network [10, 11]. To this aim, a social network is usually represented as a graph, whose nodes denote the network members and whose edges denote their relationships, which is analyzed from a structural point of view by means of methods that broadly fall into one of the following two categories: *relational analysis* methods that are often used in order to identify central members or to partition the graph into clusters, and *positional analysis* methods that examine the similarity between the connection of two network members with the other members. *Role assignment* is one of the main positional analysis methods, whose goal consists of classifying the members of a social network, so that members which are equally classified can be considered to behave in a similar way or to play a similar role [33]. If the number of roles is limited, this kind of classification can turn out to be extremely useful while trying to understand the overall structure of very complex social networks.

Importance and motivation. Our aim is applying the study of social networks to the field of heterogeneous wireless networks. Due to their nature, such networks suffer of problems such as scarce resources (bandwidth / energy supply / ...) and non homoge-

neous node functionalities. Role assignment is a possible way in order to support overlay applications, often requiring network survivability guarantee as well as specialized node functionality. Actually, several works have been recently devoted to the study of assigning roles to the nodes of sensor networks: for efficient data aggregation (and, hence, for reducing the volume of traffic carried by the network thus saving bandwidth and energy) in the wireless sensor networks; for some forms of self-configuration, where sensor nodes take on specific functions or roles in the network without manual intervention. In fact, efficiently self organizing a network hierarchy with specific assignment of roles (or tasks) to sensors based on their physical wireless connectivity and sensing characteristics is an important and challenging problem.

Related works. Computing a role assignment for a given network is equivalent to computing a coloring of the network’s nodes, such that the constraint imposed by the role assignment is satisfied by the colors assigned to the nodes. Different kinds of role assignment have been introduced in the literature. A *strong structural* role assignment, for example, imposes that if two actors play the same role, then they must have the same neighborhood [34], while a *regular* role assignment imposes that if two actors play the same role, then they must be surrounded by the same set of roles [48, 6]. In [21] we are interested in another kind of role assignment, that is, *ecological* role assignments, according to which if two network members are surrounded by the same set of roles, then they must play the same role: in other words, the role played by a social actor is completely determined by the roles played by its neighbors [7]. The relationship imposed by an ecological role assignment is the opposite of the one imposed by a regular role assignment: a role assignment that satisfies both constraints is called *perfect* [8]. As stated by Borgatti and Everett, an ecological role assignment is *easier to understand* as a model of social relationships, in which a member’s neighborhood tends to shape this member into that or this kind.

Our contribution. Given a graph $G = (V, E)$, for any node $u \in V$, $N(u)$ denotes the neighborhood of u . A *coloring* of G which uses k colors is a surjective function $r : V \rightarrow [k]$.

Given a coloring r of G which uses k colors, the *colorhood* of a node $u \in V$ with respect to r is defined as the set

$$C_r(u) = \{i \in [k] : \exists v \in N(u) [r(v) = i]\}.$$

A coloring r of a graph $G = (V, E)$ is *ecological* [7] if, for any $u, v \in V$,

$$C_r(u) = C_r(v) \Rightarrow r(u) = r(v).$$

Observe that any graph can be ecologically colored with one color. However, it is not true that any graph can be ecologically colored with n colors, where n is the number of nodes of the graph: Two nodes with the same neighborhood must be colored with the same color.

The number of distinct neighborhoods contained in a graph is thus an upper bound on the number of colors that can be used by any ecological coloring. We say that a graph $G = (V, E)$ is *neighborhood distinct* (in short, *ND*) if, for any $u, v \in V$, $N(u) \neq N(v)$.

Given a graph $G = (V, E)$, we define an equivalence relation ρ_N on the vertices of G as follows: two vertices $u, v \in V$ are equivalent if and only if $N(u) = N(v)$. The *neighborhood graph* corresponding to G is the ND graph $G_N = (V_N, E_N)$ where V_N is the set of equivalence classes with respect to the relation ρ_N , and $(x, y) \in E_N$ if all nodes in the equivalence class x are adjacent to all nodes in the equivalence class y . The *neighborhood degree* n_G of G is defined as the number of nodes in G_N . It is easy to see that: (1) A graph can be ecologically colored with k colors if and only if its neighborhood graph can be ecologically colored with k colors; (2) Each graph G can be ecologically colored with n_G colors and it cannot be ecologically colored with $k > n_G$ colors.

In [21] we prove that, for any graph G with n_G distinct neighborhoods, and for any integer k with $1 \leq k < n_G$, G admits an ecological coloring which uses exactly k colors. This coloring can be computed in polynomial time by means of a bottom-up approach.

3 Range assignment and network lifetime

Following previous work within AEOLUS, in [2] we study the problem of establishing broadcast communication from a given source node in a wireless network with the minimum energy consumption for communication; the corresponding problem is called *Minimum Energy Broadcast Routing (MEBR)*. Problems of this kind are crucial in AEOLUS in order to efficiently use wireless subnetworks as part of the overlay computer. See the survey [16] for an overview of the known results for the problem.

3.1 Definitions and related works

Formally, given a set of stations S , let $G(S)$ be the complete weighted graph whose nodes are the stations of S and in which the weight $w(x, y)$ of each edge (x, y) is the transmission power required for a direct communication between x and y . A power assignment for S is a function $p : S \rightarrow R^+$ assigning a transmission power $p(x)$ to every station in S . A power assignment p for S yields a directed communication graph $G^p = (S, A)$ such that, for each $(x, y) \in S^2$, the directed edge (x, y) belongs to A if and only if $p(x) \geq w(x, y)$, that is if x can directly transmit to y . The total cost of a power assignment is $cost(p) = \sum_{x \in S} p(x)$.

The MEBR problem for a given source $s \in S$ consists in finding a power assignment p of minimum cost such that G^p contains a directed spanning tree rooted at s (and directed towards the leaves). In general, the problem is unlikely to have polynomial-time approximation algorithms with approximation ratio $o(\ln n)$ [20], where n is the number of stations. Logarithmic (in the number of stations) approximation algorithms have been presented in [15, 18, 19]. An important case of practical interest is when stations lie in a d -dimensional Euclidean space. Then, given a constant $\alpha \geq 1$, the power consumption

needed for a correct communication between x and y is $dist(x, y)^\alpha$, where $dist(x, y)$ is the Euclidean distance between the locations of x and y . The problem has been proved to be NP-hard for $\alpha > 1$ and $d > 1$, while it is solvable in polynomial time for $\alpha = 1$ or $d = 1$ [18, 20, 12].

Several attempts in the literature have been made in order to find good approximation algorithms for Euclidean cases. A fundamental algorithm to provide an approximate solution of the MEBR problem is the MST heuristic [49]. It is based on the idea of tuning ranges so as to include a minimum spanning tree of the cost graph $G(S)$. More precisely, denote by $T(S)$ a minimum spanning tree of $G(S)$. The MST heuristic considers $T(S)$ rooted at the source station s , directs the edges of $T(S)$ towards the leaves, and sets the power $p(x)$ of every internal station x of $T(S)$ with $k > 0$ children x_1, \dots, x_k in such a way that $p(x) = \max_{i=1, \dots, k} w(x, x_i)$. In other words, p is the power assignment of minimum cost inducing the directed tree derived from $T(S)$ and is such that $cost(p) \leq c(T(S))$, where $c(T(S))$ denotes the total cost of the edges in $T(S)$. Therefore, the approximation ratio of the heuristic is bounded by the ratio between the cost of a minimum spanning tree of $G(S)$ and the optimal cost.

The performance of the MST heuristic has been investigated by several authors [1, 18, 20, 26, 32, 36, 47]. The analysis in all the above papers focuses on the case $\alpha \geq d$ (MST has unbounded approximation ratio when $\alpha < d$) and is based on elegant geometric arguments. The best known approximation ratios are 6 for $d = 2$ [1], 18.8 for $d = 3$ [36] and $3^d - 1$ for every $d > 3$ [26]. The known lower bounds [20, 47] are 6 for $d = 2$ (and, hence, the upper bound of [1] is tight), 12 for $d = 3$ and exponential for general d . Despite the considerable research effort in the area during the past years, prior to [17], no algorithm had been theoretically shown to outperform the MST heuristic in the Euclidean case, and the improvement of the corresponding ratios was a longstanding open question.

Several other heuristics have been shown to perform better than MST in practice, at least for 2-dimensional instances. The most famous among them is probably algorithm BIP (Broadcast Incremental Power [49]). Starting from the source, it builds a tree in steps as follows: at each step, it includes the edge to an uncovered station that requires the minimum increase of power. BIP has been shown to be at least as good as MST while the best known lower bound on its approximation ratio is 4.33 [47].

3.2 Experimental results

In last year's report [17], a new approximation algorithm for the MEBR problem is presented. For any instance of the problem where the minimum spanning tree of the cost graph $G(S)$ is guaranteed to cost at most ρ times the cost of an optimal solution for MEBR, the algorithm achieves an approximation ratio bounded by $2 \ln \rho - 2 \ln 2 + 2$, which exponentially improves upon the MST heuristic. Surprisingly, the algorithm and the analysis do not make use of any geometric arguments and still the results significantly improve the previously best known approximation factor for Euclidean instances of the problem. The

corresponding approximation ratio is reduced (when $\alpha \geq d$) from 6 [1] to 4.2 for $d = 2$, from 18.8 [36] to 6.49 for $d = 3$ and in general from $3^d - 1$ [26] to $2.20d + 0.61$ for $d > 3$. In the 2-dimensional case, the achieved approximation is even less than the lower bound on the approximation ratio of the BIP heuristic.

We have implemented using Matlab the algorithm of [17] as well as several variations and have experimentally compared these algorithms to the MST and BIP heuristics. A list of experiments were conducted and the results are reported in [2]. All variations of the algorithm run in time $O(n^6)$ where n is the number of points. In our experiments, we have used sets of up to 100 random points on the 2-dimensional and 3-dimensional Euclidean space. A threshold parameter (taking values between 0 and 5) has been introduced in order to slightly modify the local decisions taken by the algorithm. We point out that this parameter is fixed to 2 in the original description of the algorithm in [17]. Our results demonstrate that, at least for random points on Euclidean spaces, the best results are achieved by setting this parameter to 1.5. In this case, the energy reduction is approximately 25%. Such a reduction has not been observed for any of the existing algorithms in the literature (see [3] for a previous experimental study) including the BIP heuristic as well as more sophisticated heuristics. We have also observed an interesting behavior on the performance of the algorithm. While for values of the threshold parameter smaller than 2 the algorithm computes efficient broadcasts, for higher values the output of the algorithm is comparable to (i.e., as bad as) that of the MST heuristic.

3.3 Theoretical results: Energy consumption vs performance of the protocol

In [13, 14] the Network Lifetime and Min Energy Broadcast problems have been considered, respectively. We have introduced the first *provably good* broadcasting protocols for two important wireless scenarios.

In [13] we consider static ad-hoc wireless networks where nodes have an initial battery charge and they may dynamically change their transmission range at every time slot. When a node v transmits with range $r(v)$, its battery charge is decreased by $r(v)^2$. The goal is to provide a range assignment schedule that maximizes the number of broadcast operations from a given source (this number is denoted as the length of the schedule). This maximization problem is known to be NP-hard and the best algorithm yields worst-case approximation ratio $\Theta(\log n)$, where n is the number of nodes of the network. We consider random geometric instances formed by selecting n points independently and uniformly at random from a square of side length \sqrt{n} in the Euclidean plane. We first present an efficient algorithm that constructs a range assignment schedule having length, with high probability, not smaller than $1/12$ of the optimum. We then design an efficient distributed version of the above algorithm where nodes initially know n and their own position only. The resulting schedule guarantees the same approximation ratio achieved by the centralized

version thus obtaining the *first distributed algorithm* having provably-good performance for this problem.

In [14] we consider the MEBR problem in random-grid networks where nodes are chosen independently at random from the n points of a $\sqrt{n} \times \sqrt{n}$ square grid in the plane. The probability of the existence of a node at a given point of the grid does depend on that point, that is, the probability distribution can be *non-uniform*. By using information-theoretic arguments, we prove a lower bound $(1 - \epsilon)\frac{n}{\pi}$ on the energy cost of any feasible solution for this problem. Then, we provide an efficient solution of energy cost not larger than $1.1204\frac{n}{\pi}$.

A major challenge in this topic is to provide efficient distributed solutions. We present the *first fully-distributed protocol* that constructs a broadcast range assignment of energy cost not larger than $8n$, thus still yielding *constant* approximation. The energy load is well balanced and, at the same time, the work complexity (i.e. the energy due to all message transmissions of the protocol) is asymptotically optimal. The completion time of the protocol is only an $O(\log n)$ factor slower than the optimum. The approximation quality of our distributed solution is also experimentally evaluated. All bounds hold with probability at least $1 - 1/n^{\Theta(1)}$.

4 Quality of service for multihop wireless networks

Integrating an ad hoc wireless network, and specifically mesh networks, into an Overlay Computing Platform poses a number of challenges due to the nature of the radio medium. IEEE 802.11 is often considered as the underlying wireless technology of multihop wireless networks. But the use of 802.11 in such networks raises some issues. The two main problems concern fairness and efficiency. If some stations cannot access or cannot access correctly to the medium, these nodes can disconnect the network. Such a disconnection may affect the behaviour of the whole network or prevent some nodes from providing a given service to the overlay computer. On the other hand, if fairness and efficiency are achieved, QoS guarantees may be expected and/or provided by/for upper layer and thus for the user application of the overlay computer.

Different kinds of solutions have been proposed to overcome these problems. One approach is to design new MAC protocols that provide alternatives to the IEEE 802.11 MAC protocol and that try to increase fairness or/and efficiency in the network. Section 4.1 describes a new MAC protocol that is fully local while being fair and efficient.

Although these solutions are of some interest, it should probably take some time before new wireless network interface cards based on one of these solutions are developed and released. Moreover, as these solutions try to be as simple and local as possible (important features for a MAC protocol), it is difficult for them to tend towards a targeted fairness scheme. Another approach is to design a solution at higher layers, above IEEE 802.11, by regulating the incoming rate at the MAC layer. This regulation is achieved via a rate

allocation in order to limit the appearance of congestion and obtain a better fairness among the flows. Section 4.2 describes a rate allocation algorithm that ensures a fair distribution of bandwidth between end-to-end flows in multihop wireless networks.

4.1 SBA: A simple backoff algorithm for wireless ad hoc networks

Many researches have tackled the problem of fairness and efficiency in ad hoc networks. Most of the existing solutions provide either efficiency or fairness, but very few solutions consider both of them. The goal of our work, described in [42] is twofold: i) to design a simple backoff algorithm that is efficient and fair and ii) to study the possibilities and the limits of such a simple approach. We mean by simple that the algorithm behaviour relies only on *local information*, as successful transmissions and collisions undergone by each station without taking advantage of the carrier sensing mechanism or the packets that can be decoded. The algorithm is also simple in the sense that, contrary to the BEB algorithm, it has only two distinct contention windows. The difference between BEB and our algorithm, called hereafter *SBA* for *Simple Backoff Algorithm*, is the way of choosing the contention window to use for the packet transmission. SBA uses the same contention window for all the packets it has to send in a given time interval. At the end of this interval, some computations are done to choose the contention window for the next interval.

In SBA, we keep the main principles of the MAC protocol of the 802.11 DCF: a packet is emitted on the radio medium after a DIFS and a backoff time (during which the medium must be free) and in unicast mode, the data packet is acknowledged after a SIFS. Compared to 802.11, SBA has only two different contention windows, one large called hereafter CW_{max} and one small called CW_{min} . SBA uses local information gathered during a given time interval to adapt the contention window for the next time interval. The length of this interval must not be too short to avoid possible oscillation and not be too long to increase the reactivity of the algorithm. The time interval used in SBA is fixed and the same for all stations (denoted Δ).

The local information, known and used by a station, is the length and the time needed to transmit each packet (T_{suc} is the time spent by a station in successful transmissions and T_{col} is the time spent by the station in collisions during Δ), as the number of successful transmissions and the number of collisions it undergoes during Δ , and denoted by N_{suc} and N_{col} (resp.). From the station point of view, the medium can be occupied by other stations, or occupied by its transmission resulting in a successful transmission or in a collision, or the medium can be idle. We denote the probability for the medium to be in each state by $P[occ]$, $P[suc]$, $P[col]$ and $P[free]$ respectively. These four probabilities cannot be accurately computed by using only local information as defined previously, but they are approximated by: $P[suc] = \frac{T_{suc}}{\Delta}$, $P[col] = \frac{T_{col}}{\Delta}$, $P[free] = \frac{(N_{col} + N_{suc}) \times (cw + DIFS)}{\Delta}$ (where cw is the mean backoff time) and $P[occ] = 1 - (P[suc] + P[free] + P[col])$.

The code of SBA is presented in Algorithm 1. As we have only two states, the algorithm can be seen as the transition between these two states. Algorithm 1 shows how the

statistics gathered during the Δ period are used to adapt the contention window to use.

Algorithm 1 SBA

```

1: if ( $P[suc] \leq P[occ] + P[free]$ ) then
2:    $CW \leftarrow CW_{min}$ 
3:   if ( $P[col] > r$  && ( $\text{rand}\{0,1\}=1$ )) then
4:      $CW \leftarrow CW_{max}$ 
5:   end if
6:   if ( $(P[free] \leq s$  &&  $P[col] > 0) \parallel (N_{suc} + N_{col} = 0)$ ) then
7:      $CW \leftarrow CW_{max}$ 
8:   end if
9: else
10:   $CW \leftarrow CW_{max}$ 
11: end if

```

By simulations carried out with NS2, we compare SBA with IEEE 802.11 and several alternatives to 802.11 that solve some performance issues raised by the use of 802.11 in ad hoc networks. These results show that SBA achieves a good trade-off between fairness, efficiency and simplicity.

4.2 A practical and fair rate allocation for multihop wireless networks based on a simple node model

This work is also described in D1.5.3.

In [45], we provide a rate allocation algorithm that ensures a fair distribution of bandwidth between end-to-end flows in multihop wireless networks. It was designed with the practical aspects in mind and implemented into a protocol that was simulated under NS-2.

Most solutions require to identify maximal cliques or maximal independent sets in the wireless links contention graph [46], which is likely to be slow to compute in practice. We propose to use a simpler medium sharing model that can be directly deduced from the network topology. It is based on the fact that two nodes at carrier sensing range won't emit at the same time according to the DCF mode of IEEE 802.11. Experiments have shown that the carrier sensing range is around twice as large as the communication range obtained with slow data rates (2 or 1 Mb/s). Because of this, our model specifies that 2 nodes at a distance of 2 hops share the bandwidth.

The problem of the flow rates maximization can be written as follows:

$$\begin{aligned}
 &\text{MAXIMIZE:} && \prod_{f \in \Phi} \phi_f \\
 &\text{UNDER THE CONSTRAINTS:} && \forall n \in N \sum_{i \in V(n)} x_i \leq C
 \end{aligned} \tag{1}$$

where ϕ_f is the rate of flow f , x_i is the total bandwidth consumed by node i and $V(n)$ is the 2-hop neighbourhood of node n . $\prod_{f \in \Phi} \phi_f$ expresses the fact the we wish to maximize the rates allocated to flows while ensuring a *proportional fairness* between flows. By using Lagrangian optimization, this optimization problem can be solved in a distributed way

such that each emitting node can determine its own rate by exchanging local information with nodes in its 2-hop neighbourhood.

Implementing a rate control algorithm into a real protocol poses a number of challenges, such as limiting the overhead of the protocol and dealing with asynchronism and lost packets. So as to minimize the overhead, we have taken advantage of the Hello messages used by the AODV routing protocol and made slight changes to them so that its hello messages carry the various information our algorithm needs.

We have simulated this protocol in NS2 in various configurations, with very encouraging results:

- Although asynchronism and lost packets affect significantly the convergence speed, optimal rates are reached within 20-30 seconds in our simulations. Although these values depend a lot on the topology, these results suggest that our protocol is tractable in a real environment.
- Our protocol greatly increases the fairness of the allocations, by preventing starving flows, which is the main issue with 802.11-based ad hoc networks.

5 Bandwidth and capacity allocation in wireless mesh networks

The Round Weighting Problem, in the settings of Wireless Mesh Networks, consists in computing the most efficient allocation of bandwidth to connections. The static, or off-line, version of the problem, is defined by fixed traffic demand $f(u, v)$ for any two devices u and v in the network, and the fixed topology of the network.

The objective is to schedule radio transmissions in order to satisfy these demands, in such a way that, on average, about $f(u, v)dt$ units of traffic travel from u to v during a time interval dt . In classical wired networks, this corresponds to the multi-commodity flow problem, which has been extensively studied in the literature. In this problem, there is an undirected graph $G = (V, E)$, a capacity function $c : E \rightarrow Q^+$ and a traffic demand function $f : V \times V \rightarrow Q^+$, such that $f(u, v)$ is the amount of traffic that has to be routed from vertex u to vertex v .

A solution for this problem is a positive function Φ , such that for any path P in the graph, $\Phi(P) \in Q^+$ is the amount of traffic routed through P . Given Φ , the load (use) of an edge $e \in E$ is simply calculated as $load(e) = \sum_{P:e \in P} \Phi(P)$. Therefore, Φ is feasible if and only if $load(e) \leq c(e)$. The goal is to satisfy the demand constraints:

$$\sum_{P \in \mathcal{P}, P \text{ connecting } u \text{ to } v} \Phi(P) = f(u, v)$$

where \mathcal{P} denotes the set of all non-trivial paths in G .

Unfortunately, radio signals are subject to signal attenuation, and to interference constraints: a device cannot understand a radio transmission if the quality of the signal is

not good enough, with respect to media noise, and also to other radio signals. This means that, in radio networks, transmissions must be performed in communication steps, such that interfering transmissions do not happen at the same time. In other words, the communication resource that has to be shared, is not the set of links as in classical networks, but physical space. We model the attenuation and interference constraints of the problem, assuming that two relations are given: a transmission relation, defined over the devices in the network, and determining if a transmission from u to v is possible; and an interference model, defined over the potential transmissions, and determining which transmissions can be performed concurrently. We assume that the nodes are synchronized, and that the traffic pattern is fixed, and known in advance, or steady enough so that it can be estimated. During a communication step, some radio transmissions take place. We assume that these transmissions are successful when they do not interfere with each other. Such a pairwise non-interfering set of links is denoted as a *round*.

Summing everything up, solving the *RWP* requires to solve jointly a *multi-commodity flow problem* and a *weighted fractional coloring problem*.

In [31], we model non-interfering radio transmissions as independent sets. We then relate the complexity of round weighting to the complexity of various independent set problems (e.g. maximum weight independent set, vertex coloring, fractional coloring). These equivalence are obtained by studying the dual of the Round Weighting problem.

From this relation, we deduce that in general, round weighting is hard to approximate within $n^{1-\varepsilon}$ (n being the size of the radio network). We also provide polynomial (exact or approximation) algorithms e.g. in the following two cases: (a) when the interference constraints are specific (for instance for a network whose vertices belong to the Euclidean space), or (b) when the traffic demands are directed towards a unique node in the network (also called gathering, analogous to single commodity flow).

We also study the Euclidean-metric case and show that, in this case, the problem remains NP-hard, but admits a PTAS. Similarly, gathering instances in the graph-metric case admits a 4-approximation in general graphs. Moreover, we give an explicit formula for the optimum, when the graph is a path.

In [28], we focus on the gathering case where data are sent to the gateways, therefore the flow subproblem is a single-commodity problem. This is the core optimization of wireless mesh networks provisioning. The *RWP* input corresponds to G with the capacity c , and the network bandwidth proportion between each router and a given set of gateways. Each link of the network is allocated a capacity that is given by the flow problem solution. Simultaneously, we find a set of weighted rounds which induces the routers capacity and such that the total weight is minimized. Indeed, minimizing this weight means maximizing the bandwidth of each link, that is its capacity divided by the total weight of the rounds.

We present a mixed integer linear programming model and we use a branch-and-price algorithm to solve the problem. A column generation approach is used to avoid dealing

with the exponential set of rounds and the branch-and-bound algorithm to turn integer the flow (network packets). We run experiments on networks from the literature, with different number of gateways. Experimental results as well as theoretical insights let us conjecture that the *round-up property* holds for *RWP* considering uniform-traffic.

In [29], we give exact or almost exact bounds for the same problem in the specific case of regular grids. Under very general hypothesis on the traffic demand, we mainly prove that the throughput is determined by the bottleneck around the base station. We deal with two cases: the base station located in the center and in the corner. We use dual lower bounds and describe a protocol which is optimal when the traffic is uniform.

[35] is dedicated to a specific work about the impact of the MAC layer type on the capacity of the network. Using linear programming models, we compare the capacity of a network with MAC link per link acknowledgment to the case where the acknowledgments are done by the transport layer (TCP like).

References

- [1] C. Ambühl. An optimal bound for the MST algorithm to compute energy efficient broadcast trees in wireless networks. In *Proceeding of the 32nd International Colloquium on Automata, Languages and Programming (ICALP '05)*, LNCS 3580, Springer, pp. 1139–1150, 2005.
- [2] S. Athanassopoulos, I. Caragiannis, and C. Kaklamanis. Experimental evaluation of algorithms for energy-efficient broadcasting in ad hoc wireless networks. Technical Report, University of Patras, 2008.
- [3] S. Athanassopoulos, I. Caragiannis, C. Kaklamanis, and P. Kanellopoulos. Experimental comparison of algorithms for energy-efficient multicasting in ad hoc networks. In *Proceedings of the 3rd International Conference for Ad Hoc Networks and Wireless (ADHOC-NOW '04)*, LNCS 3158, Springer, pp. 183-196, 2004.
- [4] S.R. Blackburn and S. Gerke. Connectivity of the Uniform Random Intersection Graph. <http://www.citebase.org/abstract?id=oai:arXiv.org:0805.2814>.
- [5] M. Blonzelis. Degree Distribution of a Typical Vertex in a General Random Intersection Graph. *Lithuanian Mathematical Journal*, 48(1):38–45, 2008.
- [6] S.P. Borgatti and M.G. Everett. The class of regular equivalences: algebraic structure and computation. *Social Networks*, 11:65–88, 1989.
- [7] S.P. Borgatti and M.G. Everett. Graph colorings and power in experimental exchange networks. *Social Networks*, 14:287–308, 1992.

- [8] S.P. Borgatti and M.G. Everett. Ecological and perfect colorings. *Social Networks*, 16:43–55, 1994.
- [9] S. Boschi, P. Crescenzi, M. Di Ianni, G. Rossi, and P. Vocca. MOMOSE - A Mobility Model Simulation Environment for Mobile Wireless Ad-hoc Networks. *First International Conference on Simulation Tools and Techniques for Communications, Networks and Systems (SIMUTools)*, 2008.
- [10] U. Brandes and T. Erlebach, Eds. *Network Analysis: Methodological Foundations*. Lecture Notes in Computer Science, Vol. 3418, Springer, Berlin, 2005.
- [11] R.L. Breiger. The Analysis of Social Networks. In *Handbook of Data Analysis*, M.A. Hardy and A. Bryman, Eds. Sage Publications, London, 505–526, 2004.
- [12] M. Čagalj, J. Hubaux, and C. Enz. Minimum-energy broadcast in all-wireless networks: NP-completeness and distribution issues. In *Proceedings of the 8th Annual International Conference on Mobile Computing and Networking (MobiCom '02)*, ACM Press, pp. 172–182, 2002.
- [13] T. Calamoneri, A.E.F. Clementi, E.G. Fusco, and R. Silvestri. Maximizing the Number of Broadcast Operations in Static Random Geometric Ad-Hoc Networks. *Principles of Distributed Systems, 11th International Conference, OPODIS 2007*, LNCS 4878, pp. 247–259, 2007.
- [14] T. Calamoneri, A.E.F. Clementi, A. Monti, and R. Silvestri. Minimum-energy broadcast in random-grid ad-hoc networks: approximation and distributed algorithms. In *Proc. of the 11-th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, 2008 (to appear)
- [15] G. Calinescu, S. Kapoor, A. Olshevsky, and A. Zelikovsky. Network lifetime and power assignment in ad-hoc wireless networks. In *Proceedings of the 11th Annual European Symposium on Algorithms (ESA '03)*, LNCS 2832, Springer, pp. 114–126, 2003.
- [16] I. Caragiannis, M. Flammini, C. Kaklamanis, R. Klasing, and A. Navarra. Energy consumption minization in ad hoc wireless, and multi-interface networks. Technical Report, University of Patras, 2008.
- [17] I. Caragiannis, M. Flammini, and L. Moscardelli. An exponential improvement to the MST heuristic for minimum energy broadcasting in ad hoc wireless networks. In *Proceedings of the 34th International Colloquium on Automata, Languages, and Programming (ICALP '07)*, LNCS 4596, Springer, pp. 447–458, 2007.
- [18] I. Caragiannis, C. Kaklamanis, and P. Kanellopoulos. New results for energy-efficient broadcasting in wireless networks. In *Proceedings of the 13th Annual International Symposium on Algorithms and Computation (ISAAC '02)*, LNCS 2518, Springer, pp. 332–343, 2002.

- [19] I. Caragiannis, C. Kaklamani, and P. Kanellopoulos. Energy-efficient wireless network design. *Theory of Computing Systems*, 39(5), pp. 593–617, 2006.
- [20] A. Clementi, P. Crescenzi, P. Penna, G. Rossi, and P. Vocca. On the complexity of computing minimum energy consumption broadcast subgraphs. In *Proceedings of the 18th Annual Symposium on Theoretical Aspects of Computer Science (STACS '01)*, LNCS 2010, Springer, pp. 121–131, 2001.
- [21] P. Crescenzi, M. Di Ianni, F. Greco, G. Rossi, and P. Vocca. Making Role Assignment feasible: a polynomial-time algorithm for computing ecological colorings. In *Proc. of the 34th International Workshop on Graph-Theoretic Concepts in Computer Science (WG 2008)*, 2008 (to appear).
- [22] M. Deijfen and W. Kets. Random Intersection Graphs with Tunable Degree Distribution and Clustering. <http://www2.math.su.se/~mia/rig.pdf>.
- [23] R. Di Pietro, L.V. Mancini, A. Mei, A. Panconesi, and J. Radhakrishnan. Sensor Networks that are provably Resilient. In *2nd International Conference on Security and Privacy in Communication Networks (SecureComm)*, 2004.
- [24] C. Efthymiou and P. Spirakis. On the Existence of Hamilton Cycles in Random Intersection Graphs. In *International Colloquium on Automata, Languages and Programming (ICALP)*, 2005.
- [25] J.A. Fill, E.R. Sheinerman, and K.B. Singer-Cohen. Random Intersection Graphs when $m = \omega(n)$: An Equivalence Theorem Relating the Evolution of the $G(n, m, p)$ and $G(n, p)$ models. <http://citeseer.nj.nec.com/fill198random.html>.
- [26] M. Flammini, R. Klasing, A. Navarra, and S. Pérennes. Improved approximation results for the minimum energy broadcasting problem. In *Proceedings of ACM Joint Workshop on Foundations of Mobile Computing (DIALM-POMC)* ACM Press, pp. 85–91, 2004.
- [27] E. Godehardt and J. Jaworski. Two models of Random Intersection Graphs for Classification. *Studies in Classification, Data Analysis and Knowledge Organisation*, pp. 67–82, 2002.
- [28] C. Gomes, G. Huiban, and H. Rivano. A Branch-and-Price Approach to the Bandwidth Allocation Problem in Wireless Networks. In *International Symposium on Combinatorial Optimization (CO)*, 2008.
- [29] C. Gomes, S. Pérennes, P. Reyes, and H. Rivano. Bandwidth Allocation in Radio Grid Networks. In *10èmes Rencontres Francophones sur les Aspects Algorithmiques de Télécommunications (AlgoTel)*, 2008

- [30] M. Karoński, E.R. Scheinerman, and K.B. Singer-Cohen. On Random Intersection Graphs: The Subgraph Problem. *Combinatorics, Probability and Computing*, 8:131–159, 1999.
- [31] R. Klasing, N. Morales, and S. Pérennes. On the Complexity of Bandwidth Allocation in Radio Networks. *Theoretical Computer Science*, to appear, 2008.
- [32] R. Klasing, A. Navarra, A. Papadopoulos, and S. Perennes. Adaptive broadcast consumption (ABC), a new heuristic and new bounds for the minimum energy broadcast routing problem. In *Proceedings of the 3rd IFIP-TC6 International Networking Conference*, LNCS 3042, Springer, pp. 866–877, 2004.
- [33] J. Lerner. *Role assignments*. Chapter 9 of [10].
- [34] F. Lorrain and H.C. White. Structural equivalence of individuals in social networks. *Journal of Mathematical Sociology*, 1:49–80, 1971.
- [35] C. Molle and M.-E. Voge. Influence des acquittements sur la capacité des réseaux radio maillés. In *10èmes Rencontres Francophones sur les Aspects Algorithmiques de Télécommunications (AlgoTel'08)*, 2008
- [36] A. Navarra. 3-d minimum energy broadcasting. In *Proceedings of the 13th Colloquium on Structural Information and Communication Complexity (SIROCCO '06)*, LNCS 4056, Springer, pp. 240–252, 2006.
- [37] S. Nikolettseas, C. Raptopoulos, and P. G. Spirakis. The Existence and Efficient Construction of Large Independent Sets in General Random Intersection Graphs. In *31st International Colloquium on Automata, Languages and Programming (ICALP)*, 2004.
- [38] S. Nikolettseas, C. Raptopoulos, and P. G. Spirakis. Expander Properties and the Cover Time of Random Intersection Graphs In *32nd International Symposium on Mathematical Foundations of Computer Science (MFCS)*, 2007.
- [39] S. Nikolettseas, C. Raptopoulos, and P.G. Spirakis. Large Independent Sets in General Random Intersection Graphs. *Theoretical Computer Science (TCS) Journal, Special Issue on Global Computing*, 2008.
- [40] S. Nikolettseas, C. Raptopoulos, and P.G. Spirakis. On the Independence Number and Hamiltonicity of Uniform Random Intersection Graphs. Submitted, 2008.
- [41] C. Raptopoulos and P. Spirakis. Simple and Efficient Greedy Algorithms for Hamilton Cycles in Random Intersection Graphs. In *International Symposium on Algorithms and Computation (ISAAC)*, pp. 493–504, 2005.
- [42] T. Razafindralambo, and I. Guérin Lassous. SBA: A Simple Backoff Algorithm for Wireless Ad Hoc Networks. Research report INRIA. To appear.

- [43] K.B. Singer-Cohen. *Random Intersection Graphs*. PhD Thesis, John Hopkins University, 1995.
- [44] D. Stark. The Vertex Degree Distribution of Random Intersection Graphs. *Random Structures & Algorithms*, 24(3):249–258, 2004
- [45] R. Vannier, and I. Guérin Lassous. Towards a Practical and Fair Rate Allocation for Multihop Wireless Networks based on a Simple Node Model. Accepted to *11th ACM/IEEE International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, Vancouver, Canada, October 2008.
- [46] Y. Xue, B. Li, and K. Nahrstedt. Optimal Resource Allocation in Wireless Ad Hoc Networks: A Price-based Approach. *IEEE Transactions on Mobile Computing*, 5(4), April 2006.
- [47] P.-J. Wan, G. Calinescu, X. Li, and O. Frieder. Minimum energy broadcast routing in static ad hoc wireless networks. *Wireless Networks*, 8(6), pp. 607–617, 2002.
- [48] D.R. White and K.P. Reitz. Graph and semigroup homomorphisms on networks of relations. *Social Networks*, 5:193–234, 1983.
- [49] J.-E. Wieselthier, G.D. Nguyen, and A. Ephremides. On the construction of energy-efficient broadcast and multicast trees in wireless networks. In *Proceedings of the 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '00)*, IEEE Computer Society Press, pp. 585–594, 2000.