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Work Package 3.3: Information Theory of Wireless Networks
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This deliverable follows the first two deliverables of WP3.3, i.e. D3.3.1 where we examined suitable models (mostly stochastic) for dense interactions in large wireless networks and D3.3.2 where we pointed out and discussed several important problems and challenges arising in such networks. For these problems, and under the models chosen, we here present and discuss algorithmic solutions developed within the project.

We study two important network types that play an important role as emerging communication infrastructures: ad-hoc radio networks and wireless sensor networks. We investigate several crucial performance properties of the developed protocols, such as their correctness, efficiency, fault tolerance and scalability. We evaluate the behaviour of such protocols in very large networks of complex, dense interactions, by carrying out asymptotic analyses and large scale simulation evaluations.

1 Ad-hoc Radio Networks

We consider basic algorithms for a single-hop radio communication network. It consists of nodes (stations) communicating by exchanging radio messages, where each node is in the range of any other node. Time is divided into slots, the nodes work in a synchronous way. Within each time slot a single message may be broadcast – if more than one station broadcasts during the same time slot, then a collision occurs.

1.1 Sorting

We consider the problems of storing data in a network of nodes where each node has memory of a tiny size, as it is the case for sensor networks. So we may assume that each node can store only a single data record. In order to facilitate access to these data we sort the items according to location in the network: the $i$th node obtains the $i$th item according to some ordering. There are many possible approaches to this problem in the model of single-hop radio networks: The first generic approach is to use techniques developed for comparator networks. Each comparison of two keys requires exchange of messages between the stations storing these keys. Thus the runtime corresponds to the number of comparators in the comparator network. We are also interested in the energy efficient solutions (i.e. such that the maximum of the energy used by a single station for sending and receiving the messages is kept as small as possible.) Thus the energy cost of the simulation of comparator network is twice the maximal number of comparators connected to a single position (which is typically the depth of a comparator network).

Another approach is direct development of the algorithms designed specifically for our model of radio network. Singh and Prasanna [12] proposed sorting algorithm based on quick-sort and energetically balanced implementation of sequential selection algorithm. This algorithm sorts in time $O(n \log n)$ with energetic cost $O(\log n)$. In [9] we propose an algorithm, based on merging, sorting in time $O(n \log n)$ with energetic cost $O(\log^2 n)$ that seems to be attractive for practical applications due to its simplicity and very low constants. Paper [9] also contains description of a merging algorithm with asymptotic energetic cost $O(\log^* n)$. It is a challenging open problem, whether there exists merging algorithm with a constant energetic cost.

We also considered the case that may be expected in practice: the data size significantly exceeds the number of stations in the network. Thus each station stores a subset of $k$ keys and the length of the sorted sequence is $k \cdot n$. The simulations of comparator networks can be immediately adopted do this case by the following property. If we replace each element by a group of $k$ elements and each comparator by sorting the corresponding pair of groups, then we obtain algorithm for sorting $k \cdot n$ elements. For $k > \log n$, we propose an algorithm [11] based on the algorithmic methods from [9]. It sorts a sequence of length $k \cdot n$ stored in $n$ stations in time $O(k \cdot n)$ with energy cost $O(k \log n)$. The solution is competitive with the adaptation of the Batcher’s sorting network even for relatively small data size.
1.2 Size Approximation

One of the basic issues necessary for an ad hoc network to start its operation is to estimate its size. Otherwise it is hard either to avoid collisions or to leave unused communication channel capacity.

While size approximation algorithms based on stochastic experiments have been already developed, one of the crucial issues which has been almost completely disregarded in the algorithm design are transmission faults. Some work has been done on the hardware side – however, this approach must be limited to a “standard” fault rate. Above this level it is quite inefficient to provide immunity to transmission faults by hardware means. It should be the case that higher levels of communication protocols take care of these extraordinary situations.

Random transmission faults of physical nature are not the worst things that may happen. Since the communication channel is shared and anybody has physical access to it, a malicious user or an adversary may cause transmission faults at chosen moments. On the other hand, many classical algorithms (also those for ad hoc networks) have “hot spots”, where their efficiency depends on a faultless communication very much. For this reason such algorithms are quite fragile and easy to break down through an adversary that knows the algorithm details.

In paper [7] we present some solution for this problem. Unlike other algorithms available in the literature we consider not only estimation with an accuracy within a constant factor, but also take care of the bias of the estimation. Unexpectedly, it turns out that estimations based on median of values obtained in independent subgroups provide much better results than analogous estimations based on mean values.

Our approach yields an algorithm with a low runtime and energy cost. It can be also tuned to be robust against random communication failures and against an adversary with limited energy resources. This algorithm significantly develops solutions that were derived in the first report concerning this issue ([8]).

1.3 Broadcasting on a Highway

In [6] we propose a dynamic, ad-hoc communication network consisting of mobile units that 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 [6] we present sharper results for the multi-round size approximation algorithm than in [8]. We precisely bound deviations from the expectation value of estimated number of stations. Our proof is based on the theory of martingals and Azuma’s Inequality.

Moreover, in contrast of [8], in [6] we give mathematical proof of properties of the broadcasting algorithm instead of the experiments only. For link unreliability parameter $p_r$, we proved that $P_{i,t,x}$ – probability that a message sent in the $i$-th sector reaches $i + t$-th sector in less than $x$ rounds of the algorithm is independent from the number of stations in sectors and satisfies following inequality:

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

2 Wireless Sensor Networks

We propose algorithmic solutions for data dissemination in wireless sensor networks, trying to cope with the inherent trade-offs that arise, most importantly that of energy versus latency. We use
several algorithmic techniques, including randomization (to balance the load and to create some redundancy), local adaptation (to appropriately react to implicitly sensed local network changes), hybrid design (to combine various protocols, each of which is best suitable for particular network parameters).

2.1 Energy Balance

We continue our study in [4] for the problem of energy-balanced data propagation in wireless sensor networks. The energy balance property guarantees that the average per sensor energy dissipation is the same for all sensors in the network, during the entire execution of the data propagation protocol. This property is important since it prolongs the network’s lifetime by avoiding early energy depletion of sensors.

In [5] we generalise previous work by allowing more realistic energy assignment. A new modelisation of the process of energy consumption as a random walk along with a new analysis are proposed. Two new algorithms are presented and analysed. The first one is easy to implement and fast to execute. However, it needs a priori assumptions on the process generating data to be propagated. The second algorithm overcomes this need by inferring information from the observation of the process. Furthermore, this algorithm is based on stochastic estimation methods and is adaptive to environmental changes. This represents an important contribution for propagating energy balanced data in wireless sensor networks due to their highly dynamic nature.

More specifically, the first algorithm we propose corresponds to offline computation of the probabilities $p_i$ of transmission one hop (“slice”) towards the sink. Although very easy to implement and fast in execution it suffers from an important weakness; namely the probability of occurrence of the events per slice, i.e. the probability $p_i$ have to be known. This particularity allows very efficient computations of the probabilities $p_i$. However, this property is not realistic or at least we gain in flexibility and adaptability to devise an algorithm able to solve the problem without any assumption concerning these probabilities. The analysis of the problem leads to a formal definition of the problem of energy balanced data propagation.

The second algorithm is adaptive and based on stochastic approximation methods. The algorithm does not assume that the probabilities of occurrence of the events are known and infers their values from the observation of the events. We refer to such an algorithm as blind algorithm for energy balanced data propagation to stress the fact that there is no a priori knowledge on the statistics concerning the localisation of the events. The algorithm can be accordingly implemented on any given network and run on the fly, allowing online adaptation of the parameters of the network. This characteristic is important if the parameters of the network are prone to change (this appears frequently in sensor networks). Generally, adaptive algorithms, like the one proposed here, are most appropriate for wireless sensor networks because of their evolving nature due to dynamic properties of the networks such as sensors failures, obstacles, etc., leading to topology changes. We also formally define in a broader sense the problem of energy balanced data propagation and show formally under which conditions the problem is well formulated.

2.2 Data Propagation

Incremental deployment of heterogeneous sensors. In [1] we introduce a new modelling assumption in wireless sensor networks, that of node redeployment (addition of sensor devices during the protocol evolution) and we extend the modelling assumption of heterogeneity (having sensor devices of various types). These two features further increase the highly dynamic nature of such networks and adaptation becomes a powerful technique for protocol design. Under this model, we design, implement and evaluate a power conservation scheme for efficient data propagation.
Our protocol is adaptive: it locally monitors the network conditions (density, energy) and accordingly adjusts the sleep-awake schedules of the nodes towards best operation choices. Our protocol operates does not require exchange of control messages between nodes to coordinate.

Implementing our protocol we combine it with two well-known data propagation protocols and evaluate the achieved performance through a detailed simulation study using our extended version of ns-2. We focus in highly dynamic scenarios with respect to network density, traffic conditions and sensor node resources. We propose a new general and parameterized metric capturing the trade-off between delivery rate, energy efficiency and latency. The simulation findings demonstrate significant gains (such as more than doubling the success rate of the well-known Directed Diffusion propagation paradigm) and good trade-offs. Furthermore, redeployment of sensors during network evolution and/or heterogeneous deployment of sensors drastically improve (when compared to equal total power simultaneous deployment of identical sensors at the start) the protocol performance (i.e. the success rate increases up to four times while reducing energy dissipation and, interestingly, keeping latency low).

**Adaptive forward planning.** In [2] we present the basic design issues of the Forward Planning Situated Protocol (FPSP) for scalable, energy efficient and fault tolerant data propagation in situated wireless sensor networks. To deal with the increased complexity of such large-scale sensor systems, FPSP uses *two novel mechanisms* that allow the network operator to *adjust* the performance of the protocol in terms of energy, latency and success rate on a per-task basis. The particles react locally on environment and context changes by using *a set of rules that are based on response thresholds* that relate individual-level plasticity with network-level resiliency.

Our approach is motivated by the nature-inspired paradigm of swarm intelligence, a metaphor of social insect behavior for solving problems. This approach emphasizes distributedness, direct or indirect interactions among relatively simple agents, flexibility and robustness.

The protocol operates by employing *a series of plan & forward* phases through which devices self-organize into forwarding groups that propagate data over discovered paths. FPSP performs a limited number of *long range, high power* data transmissions to collect information regarding the neighboring devices. The acquired information, allows to *plan* a (parameterizable long) sequence of short range, low power transmissions between nearby particles, based on certain optimization criteria. All particles that decide to respond to these long range transmissions enter the *forwarding* phase during which information to the sink is propagated via the acquired plan.

This role-based approach where a selective number of devices do the high cost planning and the rest of the network operates in a low cost state leads to systems that have increased energy efficiency and high fault-tolerance since these long range planning phases allow to bypass obstacles (where no sensors are available) or faulty sensors (that have been disabled due to power failure or other natural events).

**Local optimization vs redundancy.** In [3] we investigate certain important aspects of the design, deployment and operation of distributed algorithms for data propagation in wireless sensor networks and discuss some characteristic protocols, along with an evaluation of their performance.

Because of the rather unique characteristics of sensor networks, efficient and robust distributed protocols and algorithms should exhibit the following critical properties:

- **Scalability.** Distributed protocols for sensor networks should be highly scalable, in the sense that they should operate efficiently in extremely large networks composed of huge numbers of nodes. This feature calls for an urgent need to prove by analytical means and also validate (by large scale simulations) certain efficiency and robustness (and their trade-offs) guarantees for asymptotic network sizes.
• Efficiency. Because of the severe energy limitations of sensor networks and also because of their time-critical application scenarios, protocols for sensor networks should be efficient, with respect to both energy and time.

• Fault-tolerance. Sensor particles are prone to several types of faults and unavailabilities, and may become inoperative (permanently or temporarily). Various reasons for such faults include physical damage during either the deployment or the operation phase, permanent (or temporary) cease of operation in the case of power exhaustion (or energy saving schemes, respectively). The sensor network should be able to continue its proper operation for as long as possible despite the fact that certain nodes in it may fail.

We present and discuss two representative protocols that try to avoid flooding the network, achieving good performance (with respect to time and energy) and robustness.

The basic idea of the Local Target Protocol (LTP) is to try to search for all active neighboring particles and use the information retrieved in order to forward (i.e. propagate) the data towards the neighbor that is closer to the sink (in general, to the “best”, with respect to some criterion, next hop sensor). In dense networks, such a next hop sensor can be found and LTP behaves very well. In sparse networks however, its performance drops and we have to create redundant transmissions to cope with propagation failures. In the light of this, we propose the PFR (Probabilistic Forwarding) protocol, which is inspired by the probabilistic multi-path design choice for the Directed Diffusion paradigm. The basic idea of the protocol is to minimize energy consumption by probabilistically favoring certain “good” paths (with respect to energy and time) of local data transmissions towards the sink. Thus, it creates redundant transmissions to trade-off performance and fault-tolerance.

A model and algorithm for dense, local interactions. Last year we proposed a new model for random intersection graphs \((G_{n,m,p})\). We also defined an interesting variation of the model of random intersection graphs, similar in spirit to random regular graphs. In these models each of \(n\) vertices is assigned a random subset from a fixed set of \(m\) elements, with an edge arising between two vertices when their sets have at least one common element. Because in such graphs the edges are not independent, random intersection graphs may model real-life applications (including interactions between sensors in a wireless sensor network) more accurately than classic \(G_{n,p}\) random graphs. We also proposed and analysed three algorithms for the efficient construction of large independent sets in this model. We continue this line of our research in [10] by proposing two greedy algorithms for finding hamiltonian cycles in such models. The first runs for constant \(p\) (i.e. rather dense graphs) in expected polynomial time and the second deals with smaller \(p\) and succeeds with high probability.

References


