Distributed Algorithms for Data Propagation in Deeply Networked Wireless Sensor Devices

Ioannis Chatzigiannakis Sotiris Nikoletseas Paul Spirakis

Research Academic Computer Technology Institute and Patras University
P. 0. Box 1122, 261 10 Patras, Greece.
Email: {ichatz,nikole,spirakis}@cti.gr

Abstract

Wireless sensor networks are comprised of a vast number of ultra-small fully autonomous computing, communication and sensing devices, with very restricted energy and computing capabilities, which co-operate to accomplish a large sensing task. Such networks can be very useful in practice in applications that require fine-grain monitoring of physical environment subjected to critical conditions (such as inaccessible terrains or disaster places).

Very large numbers of sensor devices can be deployed in areas of interest and use *self-organization and collaborative methods* to form deeply networked environments. Features including the huge number of sensor devices involved, the severe power, computational and memory limitations, their dense deployment and frequent failures, pose *new design and implementation aspects*. The efficient and robust realization of such large, highly-dynamic, complex, non-conventional environments is *a challenging algorithmic and technological task*.

In this paper we present 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.

Keywords: Wireless sensor networks, distributed algorithms, data propagation, performance evaluation

This work has been partially supported by the IST Programme of the European Union under contract number IST-2004-001907 (DELIS) and the Programme PYTHAGORAS under the European Social Fund (ESF) and Operational Program for Educational and Vocational Training II (EPEAEK II).

1 Introduction

Recent dramatic developments in micro-electro-mechanical (MEMS) systems, wireless communications and digital electronics have already led to the development of small in size, low-power, low-cost sensor devices. A vast number of such sensor devices that integrate sensing with wireless network interfaces, that collect and disseminate information about the physical environment, are deployed in areas of interest (e.g. inaccessible terrains, disaster places, etc.) for fine grained monitoring in different classes of applications [2]. Some typical services provided by the network are [5]: (i) *Periodic Sensing* (the sensor devices constantly monitor the physical environment and continuously report their sensors' measurements to a control center), (ii) *Event driven* (to reduce energy consumption, sensor devices monitor silently the environment and communicate to report when certain events are realized) and (iii) *Query based* (sensor devices respond to queries made by a supervising control center). Recently, new applications have been proposed, that require different approaches for disseminating sensor data to the control center, such as *Target Tracking* (where sensors exchange sensor readings in order to detect the movement pattern of a detected target) [11] or *Area Surveillance* (where sensors are equipped with video capturing devices) [17, 10].

The quality of the services provided can be measured in terms of (i) *delivery rate* (or *success rate*) that corresponds to the ratio of packets delivered to the control center over all packets generated by the sensors that correspond to a particular event, (ii) *energy dissipation rate* that captures the energy dissipated by the sensors in the process of propagating packets towards the control center and (iii) *propagation delay* (or *latency*), the time that elapsed from the realization of a particular event, to the final delivery of the message reporting it, to the control center. The importance of each of the above metrics depends on the nature of the application since there are inherent trade-offs between success rate, energy and latency. Trying to minimize *energy dissipation rate*, in an attempt to extend the lifetime of the network, by possibly forcing sensors to alternate between sleep and awake time periods [7, 22], inevitably results in increased *propagation delays.*

The efficient and robust realization of such large, highly-dynamic, complex, non-conventional, deeply networked environments is *a challenging algorithmic and technological task.* An approach for propagating information in such networks is to use routing techniques similar to those for mobile ad-hoc networks ([20]), however, the huge number of sensor devices involved, the severe power limitations, their dense deployment and frequent failures, pose *new design and implementation aspects* which are essentially different not only with respect to distributed computing and systems approaches but also to ad-hoc networking techniques.

We emphasize the following characteristic differences between sensor networks and ad-hoc networks: (i) the number of sensor particles in a sensor network is extremely large compared to that in a typical ad-hoc network, (ii) sensor networks are typically prone to faults and (iii) the limitations in energy, computational power and memory are much more severe in sensor networks. Because of faults as well as energy limitations, sensor nodes may (permanently or temporarily) join or leave the network. This leads to highly dynamic network topology changes. Because of the these 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 scenaria, 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.

2 An Abstract Model for Wireless Sensor Networks

Sensor networks are comprised of a vast number of ultra-small homogenous sensors, which we here call *particles*. Each particle is a fully-autonomous computing and communication device, characterized mainly by its available power supply (battery) and the energy cost of computation and transmission of data. Such particles (in our model here) cannot move.

We adopt here (as a starting point) a two-dimensional (plane) framework: A *wireless sensor network* (a set of grain particles) is spread in an area (for a graphical presentation, see Fig. 1). Usually the deployment of particles is done in a rather random manner (such as when particles are dropped by an airplane over the area of interest. In variations of this basic model, we may include the possibility of a (more or less) structured deployment (possibly done by humans or robots). Let n be the number of sensor particles in the area.

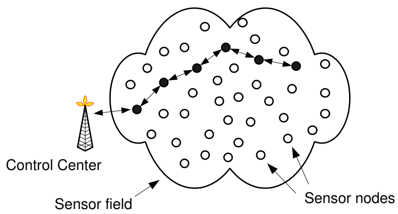

Figure 1: A Wireless Sensor Network

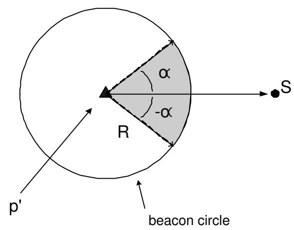

Figure 2: Directed transmission of angle α

There is a single point in the network area, which we call the sink S, that represents a control center where data should be propagated to. In variations of this basic model, there might be multiple sinks, which may be static or moving.

The particles are equipped with a set of monitors (sensors) for light, pressure, temperature etc. Each particle has a *broadcast* (digital radio) *beacon mode* which can be also a directed transmission of angle α around a certain line (possibly using some special kind of antenna, see fig. 2). The transmission range (which we denote by $\mathcal{R}$) can vary while the transmission angle (let it be α) is fixed and cannot change throughout the operation of the network (since this would require a modification or movement of the antenna used). Note that the protocols we study in this work can operate even under the broadcast communication mode (i.e. $\alpha = 2\pi$).

We believe that this model depicts accurately enough the technological specifications of real wireless sensor systems. Similar models are being used by other researchers in order to study sensor networks (see [12, 18]). The above assumptions suggest a strong model, that however does not trivialize the problem; we believe that even assuming such a model, the design of efficient distributed algorithms is still a challenging task. In contrast to [14, 15], our model is weaker in the sense that *no geolocation abilities* are assumed (e.g. a GPS device) for the particles leading to more generic and thus stronger results. In [13] a thorough comparative study and description of wireless sensor systems is given, from the technological point of view.

3 Distributed Algorithms for Data Propagation

Because of the complex nature of a sensor network (that integrates various aspects of communication and computing), protocols, algorithmic solutions and design schemes for all layers of the networking infrastructure are needed. Far from being exhaustive, we mention the need for frequency management solutions at the physical layer, for Medium Access Control (MAC) protocols to cope with multi-hop transmissions at the data link layer. The interested reader may use the excellent survey by Akyildiz et al [1] for a detailed discussion of design aspects of all layers of the networking infrastructure.

We focus in this paper on distributed algorithms for the network layer. We believe that a complementary use of rigorous analysis and large scale simulations is needed to fully investigate the performance of data propagation protocols in wireless sensor networks. In particular, asymptotic analysis may lead to provable efficiency and robustness guarantees towards the desired scalability of protocols for sensor networks that have extremely large size. On the other hand, simulation allows to investigate the effect of a great number of detailed technical specifications of real devices, a task that is difficult (if possible at all) for analytic techniques which, by their nature, use abstraction and model simplicity.

Any distributed algorithm solving the data propagation problem must satisfy the following three properties:

- **Correctness**. The distributed algorithm must guarantee that data arrives to the position S, given that the whole network exists and is operational.
- **Robustness**. The distributed algorithm must guarantee that data arrives at enough points in a small interval around S, in cases where part of the network has become inoperative.
- **Efficiency**. If the distributed algorithm activates k particles during its operation then Π should have a small ratio of the number of activated over the total number of particles $r = \frac{k}{N}$. Thus r is an energy efficiency measure of Π.

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

3.1 The Probabilistic Forwarding Protocol (PFR)

The PFR (Probabilistic Forwarding) protocol [6] is inspired by the probabilistic multi-path design choice for the Directed Diffusion paradigm mentioned in [14]. Its basic idea of the protocol (introduced in [6]) is to minimize energy consumption by *probabilistically favoring certain paths of local data transmissions towards the sink*.

The protocol *avoids flooding* by favoring (in a probabilistic manner) data propagation along sensors which lie "close" to the (optimal) transmission line, ES, that connects the sensor node detecting the event, E, and the sink, S. This is implemented by locally calculating the angle $\phi = (\widehat{EPS})$, whose corner point P is the sensor currently running the local protocol, having received a transmission from a nearby sensor, previously possessing the event information. If ϕ is equal or greater to a predetermined threshold ($\phi_{threshold}$), then p will transmit (and thus propagate the event information further). Else, it decides whether to transmit with probability equal to $\frac{\phi}{\pi}$. Because of the probabilistic nature of data propagation decisions and in order to prevent the data propagation process from early failing, we initially use (for a short time period which we evaluate) a flooding mechanism that leads to a sufficiently large *"front"* of sensors possessing the data under propagation. When such a "front" is created, we perform probabilistic forwarding.

Note that transmission along this line is energy optimal. However it is not always possible to achieve this optimality, basically because certain sensors on this direct line might be inactive, either permanently (because their energy has been exhausted) or temporarily (because these sensors might enter a sleeping mode to save energy). Further reasons include (a) physical damage of sensors, (b) deliberate removal of some of them (possibly by an adversary in military applications), (c) changes in the position of the sensors due to a variety of reasons (weather conditions, human interaction etc). and (d) physical obstacles blocking communication.

Essentially, PFR captures the intuitive, deterministic idea "if my distance from ES is small, then send, else do not send". This idea was enhanced by random decisions (above a threshold) to allow some local flooding to happen with small probability and thus to cope with local sensor failures.

Performance Evaluation. In [6] the authors prove the correctness of the PFR protocol, by using a geometric analysis: PFR always propagates data to the sink, under ideal network conditions (no failures), thus it is provably correct. Using properties of stochastic processes, it is shown that the protocol is very energy efficient. Also, when part of the network is inoperative (which is more realistic, because sensors are prone to faults), the protocol manages to propagate data very close to the sink, thus it is robust.

Note that the number of steps in the forwarding phase of the protocol depends on the $\phi_{threshold}$ of the protocol as it can be seen from the analysis in [6]. For $\phi_{threshold} = 134^o$ the number of flooding steps must be at least $180\sqrt{2}$ for correctness reasons. We can increase the $\phi_{threshold}$; this will increase also the number of flooding steps. This also implies a tradeoff between energy efficiency and robustness.

The energy efficiency of the PFR protocol is $\Theta\left(\left(\frac{n_0}{n}\right)^2\right)$ where $n_0 = |ES|$ and $n = \sqrt{N}$, where N is the number of particles in the network. For $n_0 = |ES| = o(n)$, this is $o(1)$. In order to prove the energy efficiency of PFR, let consider the area around the ES line, whose particles participate in the propagation process. The number of active particles is thus, roughly speaking, captured by the size of this area, which in turn is equal to $|ES|$ times the maximum distance from $|ES|$ (where maximum is over all active particles).

This maximum distance is clearly a random variable. To calculate the expectation and variance of this variable, the authors in [6] basically "upper bound" the stochastic process of the distance from ES by a random walk on the line, and subsequently "upper bound" this random walk by a well-known stochastic process (i.e. the "discouraged arrivals" birth and death Markovian process, see e.g. [16]).

In order to evaluate the robustness of PFR lets consider particles "very near" to the ES line. Clearly, such particles have large ϕ-angles (i.e. $\phi > 134^o$). Thus, even in the case that some of these particles are not operating, the probability that none of those operating transmits (during the probabilistic phase 2) is very small. In particular, in [6] it is shown that PFR manages to propagate the crucial data across lines parallel to ES, and of constant distance, with *fixed* nonzero probability (not depending on n, $|ES|$).

3.2 The Local Target Protocol (LTP)

We now present the LTP protocol [8] for wireless sensor networks. The basic idea of the protocol is to try to *search* for all active neighboring particles and in the sequence use the information retrieved in order to *forward* (i.e. propagate) the data towards the neighbor that is closer to the sink. In this protocol, each particle p' that has received *info($\mathcal{E}$)* from p (via, possibly, other particles) does the following:

> **Phase 1: The Search Phase.** It uses a periodic low energy broadcast of a beacon in order to discover a particle nearer to $\mathcal{S}$ than itself. Among the particles returned, p' selects a unique particle p'' that is "best" with respect to progress towards the sink, that is, the particle p''_E that among all particles found achieves the bigger progress on the $p'S$ line, should be selected.
>
> **Phase 2: The Direct Transmission Phase.** Then, p' sends *info($\mathcal{E}$)* to p'' and sends a *success* message to p (i.e. to the particle that it originally received the information from).
>
> **Phase 3: The Backtrack Phase.** If consecutive repetitions of the *search phase* fail to discover a particle nearer to $\mathcal{S}$, then p' sends *fail* message to the particle that it originally received the information from.

In the above procedure, propagation of *info($\mathcal{E}$)* is done in two steps; (i) particle p' locates the next particle (p'') and transmits the information and (ii) particle p' waits until the next particle (p'') succeeds in propagating the message further towards $\mathcal{S}$. This is done to speed up the backtrack phase in case p'' does not succeed in discovering a particle nearer to $\mathcal{S}$.

Note that one can estimate an a-priori upper bound on the number of repetitions of the search phase needed, by calculating the probability of success of each search phase, as a function of various parameters (such as density, search angle, transmission range). This bound can be used to decide when to backtrack.

Performance Evaluation. In [8], the "hops" efficiency of LTP is evaluated as a ratio of the number of transmissions required to reach the sink Sover the "optimal" (direct to S) transmissions needed to reach Sin the *ideal* case in which particles alwasy exist in pair-wise distances $\mathcal{R}$ on the vertical line from p to $\mathcal{S}$. Remark that $h_{opt} = \left\lceil \frac{d(p,\mathcal{S})}{\mathcal{R}} \right\rceil$, where $d(p, \mathcal{S})$ is the distance of p from the sink $\mathcal{S}$. Clearly, the number of hops (transmissions) needed characterizes the energy consumption and the time needed to propagate the information $\mathcal{E}$ to the sink.

In the case where the protocol Π is randomized, or in the case where the distribution of the particles in the cloud is a random distribution, the number of hops h and the efficiency ratio C_h are random variables and one wishes to study their expected values.

To enable a first step towards a rigorous analysis of smart dust protocols, [8] makes the following simplifying assumption: *The search phase always finds a* p'' (of sufficiently high battery) in the semicircle of center the particle p' currently possessing the information about the event and radius $\mathcal{R}$, in the direction towards $\mathcal{S}$. Note that this assumption on always finding a particle can be relaxed in the following ways: (a) by repetitions of the search phase until a particle is found. This makes sense if at least one particle exists but was sleeping during the failed searches, (b) by considering, instead of just the semicircle, a cyclic sector defined by circles of radiuses $\mathcal{R} - \Delta\mathcal{R}$, $\mathcal{R}$ and also take into account the density of the smart cloud, (c) if the protocol during a search phase ultimately fails to find a particle towards the sink, it may *backtrack*.

[8] also assumes that the position of p'' is uniform in the arc of angle $2a$ around the direct line from p' vertical to $\mathcal{S}$. Each data transmission (one hop) takes constant time t (so the "hops" and time efficiency of our protocols coincide in this case). It is also assumed that each target selection is stochastically *independent* of the others, in the sense that it is always drawn uniformly randomly in the arc $(-\alpha, \alpha)$.

The above assumptions may not be very realistic in practice, however, they can be relaxed and in any case allow to perform a first effort towards providing some concrete analytical results.

Lemma 3.1 ([8]) *The expected "hops efficiency" of the local target protocol in the a-uniform case is*

$$E(C_h) \simeq \frac{\alpha}{\sin\alpha}$$

for large h_{opt}. Also

$$1 \le E(C_h) \le \frac{\pi}{2} \simeq 1.57$$

for $0 \le \alpha \le \frac{\pi}{2}$.

Proof: Due to the protocol, a sequence of points is generated, $p_0 = p, p_1, p_2, \ldots, p_{h-1}, p_h$ where p_{h-1} is a particle within $\mathcal{S}$'s range and p_h is part of the sink. Let α_i be the (positive or negative) angle of p_i with respect to p_{i-1}'s vertical line to $\mathcal{S}$. It is:

$$\sum_{i=1}^{h-1} d(p_{i-1}, p_i) \le d(p, \mathcal{S}) \le \sum_{i=1}^{h} d(p_{i-1}, p_i)$$

Since the (vertical) progress towards $\mathcal{S}$ is then $\Delta_i = d(p_{i-1}, p_i) = \mathcal{R}\cos\alpha_i$, we get:

$$\sum_{i=1}^{h-1} \cos\alpha_i \le h_{opt} \le \sum_{i=1}^{h} \cos\alpha_i$$

From Wald's equation for the expectation of a sum of a random number of independent random variables (see [21]), then

$$E(h-1) \cdot E(\cos\alpha_i) \le E(h_{opt}) = h_{opt} \le E(h) \cdot E(\cos\alpha_i)$$

Now, $\forall i$, $E(\cos\alpha_i) = \int_{-\alpha}^{\alpha} \cos x \, \frac{1}{2\alpha} dx = \frac{\sin\alpha}{\alpha}$. Thus

$$\frac{\alpha}{\sin\alpha} \le \frac{E(h)}{h_{opt}} = E(C_h) \le \frac{\alpha}{\sin\alpha} + \frac{1}{h_{opt}}$$

Assuming large values for h_{opt} (i.e. events happening far away from the sink, which is the most interesting case in practice since the detection and propagation difficulty increases with distance) we have (since for $0 \le \alpha \le \frac{\pi}{2}$ it is $1 \le \frac{\alpha}{\sin\alpha} \le \frac{\pi}{2}$) and the result follows.

■

In order to further study the performance of LTP, [8] investigates the possibility where the protocol carries out more than one search phase and now assumes that these sequential phases always return *two points* p'', p''' each uniform in $(-\alpha, \alpha)$. They call this variation of LTP the "min-two uniform targets" protocol (M2TP). Now, the protocol selects the best of the two points, with respect to the local (vertical) progress. This is in fact an optimized version of the Local Target Protocol.

In a similar way as in the proof of the previous lemma, the authors prove the following result:

Lemma 3.2 ([8]) *The expected "hops efficiency" of the "min two uniform targets" protocol in the a-uniform case is*

$$E(C_h) \simeq \frac{\alpha^2}{2(1-\cos\alpha)}$$

for $0 \leq \alpha \leq \frac{\pi}{2}$ *and for large* h.

Now remark that

$$\lim_{\alpha\to 0} E(C_h) = \lim_{\alpha\to 0} \frac{2\alpha}{2\sin a} = 1$$

and

$$\lim_{\alpha\to\frac{\pi}{2}} E(C_h) = \frac{(\pi/2)^2}{2(1-0)} = \frac{\pi^2}{8} \simeq 1.24$$

Thus, [8] proves the following:

Lemma 3.3 ([8]) *The expected "hops" efficiency of the min-two uniform targets protocol is*

$$1 \leq E(C_h) \leq \frac{\pi^2}{8} \simeq 1.24$$

for large h *and for* $0 \leq \alpha \leq \frac{\pi}{2}$.

Remark that, with respect to the expected hops efficiency of the local target protocol, the min-two uniform targets protocol achieves, because of the one additional search, a relative gain which is $(\pi/2 - \pi^2/8)/(\pi/2) \simeq 21.5\%$.

4 Some Recent Work

In [9], the problem of *energy-balanced* data propagation in wireless sensor networks is studied. 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.

They propose a *new algorithm* that in each step decides whether to propagate data one-hop towards the final destination (the sink), or to send data directly to the sink. This randomized choice balances the (cheap) one-hop transimssions with the direct transimissions to the sink, which are more expensive but *"bypass" the sensors lying close to the sink.* Note that, in most protocols, these close to the sink sensors tend to be overused and die out early.

By a detailed analysis they *precisely estimate* the probabilities for each propagation choice in order to guarantee energy balance. The needed estimation can easily be performed by current sensors using simple to obtain information. Under some assumptions, they also derive a *closed form* for these probabilities.

The fact (shown by the analysis) that direct (expensive) transmissions to the sink are needed only rarely, shows that their protocol, besides energy-balanced, is *also energy efficient.*

In [3], the authors propose a new energy efficient and fault tolerant protocol for data propagation in smart dust networks, the Variable Transmission Range Protocol (VTRP). The basic idea of data propagation in VTRP is the varying range of data transmissions, ie. they allow the transmission range to increase in various ways. Thus data propagation in the protocol exhibits high fault-tolerance (by bypassing obstacles or faulty sensors) and increases network lifetime (since critical sensors, ie. close to the control center are not overused). As far as we know, it is the first time varying transmission range is used.

In [19] *extended versions* of two data propagation protocols are presented: the Sleep-Awake Probabilistic Forwarding Protocol (SW-PFR) and the Hierarchical Threshold sensitive Energy Efficient Network protocol (H-TEEN). These non-trivial extensions aim at improving the performance of the original protocols, by introducing *sleep-awake periods* in the PFR protocol to save energy, and introducing a *hierarchy of clustering* in the TEEN protocol to better cope with large networks areas. b) They have *implemented* the two protocols and performed an *extensive experimental comparison* (using simulation) of various important measures of their performance with a focus on energy consumption. c) They investigate in detail the *relative advantages and disadvantages* of each protocol and discuss and explain their behavior. d) In the light above they propose and discuss a possible *hybrid combination of the two protocols* towards optimizing certain goals.

Recently, [4] propose a novel and efficient energy-aware distributed heuristic, which they refer to as EAD, to build a special rooted broadcast tree with many leaves that is used to facilitate data-centric routing in wireless microsensor networks. EAD algorithm makes no assumption on local network topology, and is based on residual power. It makes use of a *neighboring broadcast scheduling* and *distributed competition among neighboring nodess.*

EAD basically computes a tree with many leaves. With the transceivers of all leaf nodes being turned off, the network lifetime can be greatly extended. In [4] EAD scheme is implemented and an extensive simulation experiments is conducted to study the its performance. The experimental results indicate clearly that EAD scheme outperforms previous schemes, such as LEACH among other protocols.

References

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, *A survey on sensor networks*, IEEE Communications Magazine (2002), 102–114.

[2] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, *Wireless sensor networks: a survey*, Journal of Computer Networks **38** (2002), 393–422.

[3] T. Antoniou, A. Boukerche, I. Chatzigiannakis, G. Mylonas, and S. Nikoletseas, *A new energy efficient and fault-tolerant protocol for data propagation in smart dust networks using varying transmission range*, 37th Annual Simulation Symposium (ANSS 2004), 2004, IEEE Press, pp. 43–52.

[4] A. Boukerche, X. Cheng, and J. Linus, *Energy-aware data-centric routing in microsensor networks*, ACM Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM 2003) (Paris, France), 2003, pp. 42–49.

[5] A. Boukerche, R.W.N. Pazzi, and R.B. Araujo, *A supporting protocol to periodic, event-driven and query-based application scenarios for critical conditions surveillance*, 1st International Workshop on Algorithmic Aspects of Wireless Sensor Networks (ALGOSENSORS 2004), Springer-Verlag, 2004, Lecture Notes in Computer Science, LNCS 3121, pp. 137–146.

[6] I. Chatzigiannakis, T. Dimitriou, S. Nikoletseas, and P. Spirakis, *A probabilistic forwarding protocol for efficient data propagation in sensor networks*, 5th European Wireless Conference on Mobile and Wireless Systems beyond 3G (EW 2004), 2004, pp. 344–350.

[7] I. Chatzigiannakis and S. Nikoletseas, *A sleep-awake protocol for information propagation in smart dust networks*, 3rd International Workshop on Mobile, Ad-hoc and Sensor Networks (WMAN 2003), 2003, IPDPS Workshops, p. 225.

[8] I. Chatzigiannakis, S. Nikoletseas, and P. Spirakis, *Smart dust protocols for local detection and propagation*, 2nd ACM International Annual Workshop on Principles of Mobile Computing (POMC 2002), 2002, pp. 9–16.

[9] C. Efthymiou, J. Rolim, and S. Nikoletseas, *Energy balanced data propagation in wireless sensor networks*, 4th International Workshop on Mobile, Ad-hoc and Sensor Networks (WMAN 2004), 2004, IPDPS Workshops, p. 225.

[10] W. Feng, B. Code, C. Kaiser, M. Shea, and W. Feng, *Panoptes: Scalable low-power video sensor networking technologies*, ACM Multimedia, 2003, pp. 562–571.

[11] C. Gui and P. Mohapatra, *Power conservation and quality of surveilance in target tracking sensor networks*, 10th ACM/IEEE Annual International Conference on Mobile Computing (MOBICOM 2004) (Philadelphia, USA), 2004, pp. 129–143.

[12] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, *Energy-efficient communication protocol for wireless microsensor networks*, 33rd IEEE Hawaii International Conference on System Sciences (HICSS 2000), 2000, p. 8020.

[13] S.E.A. Hollar, *Cots dust*, Msc. thesis, Engineering-Mechanical Engineering, University of California, Berkeley, USA, 2000.

[14] C. Intanagonwiwat, R. Govindan, and D. Estrin, *Directed diffusion: A scalable and robust communication paradigm for sensor networks*, 6th ACM/IEEE Annual International Conference on Mobile Computing (MOBICOM 2000), 2000, pp. 56–67.

[15] B. Karp, *Geographic routing for wireless networks*, Ph.D. dissertation, Harvard University, Cambridge, USA, 2000.

[16] L. Kleinrock, *Queueing systems, theory*, vol. I, John Wiley & Sons, 1975.

[17] W. Kumwilaisak, Y.T. Hou, Q. Zhang, W. Zhu, C.C.J. Kuo, and Y.Q. Zhang, *A cross-layer quality of service mapping architecture for video delivery in wireless networks*, IEEE Journal on Selected Areas in Communications **21** (2003), no. 10, 1685–1689.

[18] A. Manjeshwar and D.P. Agrawal, *TEEN: A routing protocol for enhanced efficiency in wireless sensor networks*, 2nd International Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing (WPIM 2002), 2002, IPDPS Workshops, p. 195b.

[19] S. Nikoletseas, I. Chatzigiannakis, H. Euthimiou, A. Kinalis, T. Antoniou, and G. Mylonas, *Energy efficient protocols for sensing multiple events in smart dust networks*, 37th Annual Simulation Symposium (ANSS 2004), 2004, IEEE Press, pp. 15–24.

[20] C.E. Perkins, *Ad hoc networking*, Addison-Wesley, Boston, 2001.

[21] S.M. Ross, *Stochastic processes*, 2nd ed., John Wiley and Sons, Inc., 1995.

[22] C. Schurgers, V. Tsiatis, S. Ganeriwal, and M. Srivastava, *Topology management for sensor networks: Exploiting latency and density*, 3rd IEEE/ACM Annual International Symposium on Mobile Ad Hoc Networking & Computing (MOBIHOC 2002), 2002, pp. 135–145.