# Smart Dust Protocols for Local Detection and Propagation *

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**Abstract**

Smart Dust is a set of a vast number of ultra-small fully autonomous computing and communication devices, with very restricted energy and computing capabilities, that co-operate to quickly and efficiently accomplish a large sensing task. Smart Dust can be very useful in practice i.e. in the local detection of a remote crucial event and the propagation of data reporting its realization. In this work we open the research on smart dust from a basic algorithmic point of view. We first provide a simple but realistic model for smart dust and present an interesting problem, which is how to propagate efficiently an event detected locally. Then we present a set of smart dust protocols for local detection and propagation that are simple enough to be implemented on real smart dust systems, and perform a rigorous average case analysis of their efficiency and energy consumption (and their interplay). This analysis leads to concrete results showing that our protocols are very efficient.

Due to lack of space, some text is included in a clearly marked Appendix that may be read at the discretion of the Program Committee.

## 1 Introduction

Networked sensors (or Smart Dust) are very large systems, comprised of a vast number of ultra-small fully autonomous computing and communication devices that cooperate to achieve a large sensing task. Examining each such single device individually, might appear to have small utility. The realization of Smart Dust however, lies in using and co-ordinating a vast number of such devices.

Smart Dust is a useful case of dynamic environments of networked sensors that are spread over a global system and try to communicate and compute efficiently and quickly, having only partial knowledge of the global conditions and having poor energy and computing resources. Designing protocols to coordinate such systems (i.e. create a dynamic and efficient network of these sensors) and monitoring their behaviour as they operate in complex and dynamic global environments is of great importance for information gathering and processing in many practical situations.

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As an example, [6] report that integrated low-power sensing devices will permit remote object monitoring and tracking in inhospitable physical environments such as remote geographic regions or toxic

urban locations. They will also enable low maintenance sensing in the field (vehicles, equipment, personnel), the office buildings (projectors, furniture, books, people), the factory floor (motors, small robotic devices).

To motivate the challenges in designing such sensor networks, we can consider the following scenario where local detection and fast propagation to the authorities of the realization of a crucial event can be achieved using smart dust. Think about thousand of disposable sensors scattered (e.g. thrown from an aircraft) over a forest. Each of these sensors can monitor the temperature at a single, very small geographical area. The sensors coordinate to establish an efficient, dynamic and short-lived communication network, dividing the task of monitoring the terrain and offering continuous monitoring of the environment in order to alert the authorities as soon as possible after a forest fire is detected by some sensor.

Several aspects of such systems of autonomous networked entities emerge, which are quite different from those posed by standard computer networks. Such aspects include the very poor and highly restricted resources (e.g. very low battery power, low computing capabilities, total absence of synchrony and anonymity).

This work is an attempt towards capturing the underlying foundational and algorithmic issues in the design of such systems, abstracting accurately enough the real technological specifications involved and providing some first concrete results for the efficiency of a variety of smart dust protocols using an average case analysis. It continues the long-term target of our team to characterize the algorithmic capabilities of non-conventional networks (e.g. ad-hoc mobile networks [3, 4]), which emerge as a result of advanced technology and deviate significantly from the classical ones.

We focus in this paper on the efficient use of smart dust in local detection and propagation protocols. We first provide an abstract model for smart dust systems which is simple enough to allow an analysis to develop, being however at the same time quite realistic, in terms of the technological specifications of real smart dust systems it captures. Then we define the problem of local detection and propagation using smart dust and also propose some concrete measures for the average case analysis of protocols for this problem.

**Our Results:** For the local detection and propagation problem using smart dust, we provide a set of four protocols. All protocols are simple enough to be implemented in real smart dust systems despite the severe energy and computing power limitations of such systems. Furthermore, we give a rigorous average case analysis for the efficiency of these protocols. We consider a variety of performance and robustness criteria, such as propagation time, number of particle to particle transmissions (which characterizes the energy consumption) and fault-tolerance. These alternative protocols we propose represent different trade-offs between these criteria and their interplay.

1. Our first protocol, which we call the "local target protocol", uses a fast and cheap search phase which is assumed to always return a nearby particle towards the authorities, uniformly in some range. It achieves a propagation time and an energy consumption whose expected ratio over the optimal solutions is at most $\pi/2 \simeq 1.57$.

2. Our second protocol (the "min-two uniform targets" protocol) applies the simple idea of getting at least two particles towards the authorities and selecting the best. It is in fact an optimized version of the local target protocol, and has an expected time and energy ratio over the optimal solutions which is at most $\pi^2/8 \simeq 1.24$.

3. Next we provide tight upper bounds to the number of particle to particle data transmissions distribution of a generalized target protocol.

4. Our next protocol (which we call the "RETRY" protocol) attempts a trade-off between taking any progress in a single search, or waiting to find a better solution in an additional search. It can be appropriately adapted to obtain a desired trade-off between the time efficiency and the energy consumption of the protocol.

5. Finally, our last protocol (which we call the "SLEEP-AWAKE" protocol) allows the proper setting of the technological specifications of a smart dust system (such as the density and the energy saving mode of the smart dust particles) as well as the propagation time, in order to achieve certain fault-tolerance guarantees.

**Related Work:**

A family of negotiation-based information dissemination protocols suitable for wireless sensor networks is presented in [9]. Sensor Protocols for Information via Negotiation (SPIN) focus on the efficient dissemination of individual sensor observations to all the sensors in a network. However, in contrast to classic flooding, in SPIN sensors negotiate with each other about the data they possess using meta-data names. These negotiations ensure that nodes only transmit data when necessary, reducing the energy consumption for useless transmissions. To assess the efficiency, a comparative simulation-based study is performed versus flooding and gossiping protocols, where SPIN protocols as shown to achieve high performance at a low cost in terms of data dissemination per unit energy.

A data dissemination paradigm called *directed diffusion* for sensor networks is presented in [10], where data-generated by sensor nodes is named by attribute-value pairs. An observer requests data by sending *interests* for named data; data matching the interest is then "drawn" down towards that node by selecting a single path or through multiple paths based on data-centric criteria. The authors assume that sensors are equipped with fully-functional GPS receivers that provide absolute location information and mechanisms for time synchronization, have a data memory amounting to several tens of MBytes and are provided with a unique identifiers.

We note that, as opposed to the work presented in this paper, the research in [9, 10] contains just technical design specifications, as efficiency issues are either not considered at all or only experimentally studied and no analysis is given.

## 2 The Model

Smart dust is comprised of a vast number of ultra-small sensors, which we call "grain" particles. Each smart-dust *grain 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 cannot move.

Each particle is equipped with a set of monitors (sensors) for light, pressure, humidity, temperature etc. Each particle has two communication modes: a *broadcast* (digital radio) *beacon mode* (for low energy - short signals) and a *directed to a point* actual data transmission mode (usually via a laser beam). Also, in a variation of our model capturing energy saving specifications, each particle may alternate (independently of other particles) between a *sleeping* and an *awake* mode. During sleeping periods grain particles cease any communication with the environment, thus they are unable to listen, receive and propagate data transmitted by other particles. However, the sleeping particles are able to sense any changes in their environment and thus are able to wake upon sensing a crucial event (see [8]).

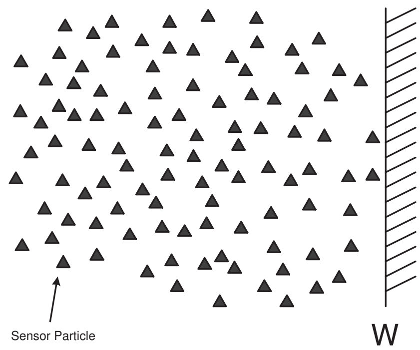


Figure 1: A Smart Dust Cloud

We adopt here a two-dimensional (plane) framework: A *smart dust cloud* (a set of particles) is spread in an area.

**Definition 2.1** Let $d$ (usually measured in numbers of $particles/m^2$) be the *density* of particles in the area.

**Definition 2.2** Let $R$ be the maximum (beacon/laser) transmission range of each grain particle.

We assume that each smart-dust particle has individually *a sense of direction* (e.g. a GPRS and also through its magnetometer sensor).

**Definition 2.3** A *receiving wall* $\mathcal{W}$ is defined to be an infinite line in the smart-dust plane. Any particle transmission within range $R$ from the wall $\mathcal{W}$ is received by $\mathcal{W}$.

We assume that $\mathcal{W}$ has very strong computing power, able to collect and analyze received data. The wall represents in fact the authorities who the realization of a crucial event should be reported to.

We feel that our model, although simple, depicts accurately enough the technological specifications of real smart dust systems. In [8] a thorough comparative study and description of smart dust systems is given, from the technological point of view. In the Appendix we report some basic technical characteristics which we took into account when defining the model of smart dust we use here.

# 3 The Problem

An *adversary* $A$ selects a single particle, $p$, in the plane-cloud and allows it to monitor a *local crucial event* $\mathcal{E}$. The general *propagation problem* $\mathcal{P}$ is the following:

> "How can particle $p$, via cooperation with the rest of the cloud, propagate information about event $\mathcal{E}$ to the receiving wall $\mathcal{W}$?"

**Definition 3.1** Let $h_{opt}(p, \mathcal{W})$ be the (optimal) number of "hops" (direct, vertical to $\mathcal{W}$ transmissions) needed to reach the wall, in the *ideal* case in which particles always exist in pair-wise distances $R$ in the vertical line from $p$ to $\mathcal{W}$.

**Definition 3.2** Let $\pi$ be *a smart-dust propagation protocol*, using *a transmission path* of length $L(\pi, p, \mathcal{W})$ to send info about event $\mathcal{E}$ to wall $\mathcal{W}$. Let $h(\pi, p, \mathcal{W})$ be the number of hops (transmissions) taken to reach $\mathcal{W}$.

**Definition 3.3** The *"hops" efficiency* of protocol $\pi$ is the ratio

$$C_h = \frac{h(\pi, p, \mathcal{W})}{h_{opt}(p, \mathcal{W})}$$

Clearly, the number of hops (transmissions) needed characterizes the energy consumption and the time needed to propagate the information $\mathcal{E}$ to the wall. Remark that $h_{opt} = \left\lceil \frac{d(p,\mathcal{W})}{R} \right\rceil$, where $d(p, \mathcal{W})$ is the (vertical) distance of $p$ from the wall $\mathcal{W}$.

In the case where protocol $\pi$ 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 we study here their expected values.

The reason behind these definitions is that when $p$ (or any intermediate particle in the information propagation to $\mathcal{W}$) "looks around" for a particle as near to $\mathcal{W}$ as possible to pass its information about $\mathcal{E}$, it may not get any particle in the perfect direction of the line vertical to $\mathcal{W}$ passing from $p$. This difficulty comes mainly from three causes: a) Due to the initial spreading of particles of the cloud in the area and because particles do not move, there might not be any particle in that direction. b) Particles of *sufficient remaining* battery power may not be available in the right direction. c) Particles may temporarily "sleep" (i.e. not listen to transmissions) in order to save battery power.

**Remark:** Note that any given distribution of particles in the smart dust cloud may not allow the ideal optimal number of hops to be achieved at all. In fact, the least possible number of hops depends on the input (the positions of the grain particles). We have chosen, however, to compare the efficiency of our protocols to the ideal case. A comparison with the best achievable number of hops in each input case will of course give better efficiency ratios for our protocols.

# 4 The Local Target Protocol

Let $d(p_i, p_j)$ the distance (along the corresponding vertical lines towards $\mathcal{W}$) of particles $p_i$, $p_j$ and $d(p_i, \mathcal{W})$ the (vertical) distance of $p_i$ from $\mathcal{W}$.

Let *info($\mathcal{E}$)* the information about the realization of the crucial event $\mathcal{E}$ to be propagated. In this protocol, each particle $p'$ that has received *info($\mathcal{E}$)* from $p$ (via, possibly, other particles) does the following:

- *Search Phase*: It uses a periodic low energy broadcast of a beacon in order to discover a particle nearer to $\mathcal{W}$ than itself. (i.e. a particle $p''$ where $d(p'', \mathcal{W}) < d(p', \mathcal{W})$).
- *Direct Transmission Phase*: Then, $p'$ sends *info($\mathcal{E}$)* to $p''$ via a direct line (laser) time consuming transmission.

Note that the maximum distance $d(p', p'')$ is $R$, i.e. the beacon transmission range.

**A simple case - The Uniform Target.** We assume here the following simple case: *The search phase takes zero time* and always finds a $p''$ (of sufficiently high battery) in the semicircle of

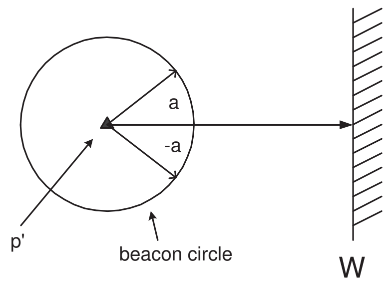


Figure 2: Example of the Search Phase

center $p$, in the direction towards $\mathcal{W}$. We also assume that the position of $p''$ is uniform in the arc of angle $2a$ around the direct line from $p'$ vertical to $\mathcal{W}$. Each data transmission (one hop) takes constant time $t$ (so the "hops" and time efficiency of our protocols coincide in this case).

We also assume that each target selection is random *independent* of the others, in the sense that it is always drawn uniformly in the arc $(-a,\, a)$.

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 $\mathcal{W}$'s range and $p_h$ is part of the wall. Let $\alpha_i$ be the (positive or negative) angle of $p_i$ with respect to $p_{i-1}$'s vertical line to $\mathcal{W}$. It is:

$$\sum_{i=1}^{h-1} d(p_{i-1},\, p_i) \;\leq\; d(p,\, \mathcal{W}) \;\leq\; \sum_{i=1}^{h} d(p_{i-1},\, p_i)$$

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

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

From Wald's equation for the expectation of a sum of a random number of independent random variables (see [1, 5]), then

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

Now, $\forall i$,

$$E(\cos\alpha_i) \;=\; \int_{-\alpha}^{\alpha} \cos x \,\frac{1}{2\alpha} dx \;=\; \frac{\sin\alpha}{\alpha}$$

Thus

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

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

**Lemma 4.1** *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* $1 \leq E(C_h) \leq \frac{\pi}{2} \simeq 1.57$*, for* $0 \leq \alpha \leq \frac{\pi}{2}$*.*

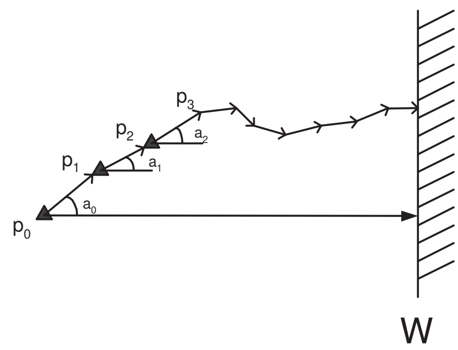


Figure 3: Example of a Transmission

## 5 Local Optimization - The "min two uniform targets" Protocol

Note that the same basic framework holds for any situation in which the local (vertical) progress in the direction towards $\mathcal{W}$ (i.e. $\Delta_i$) is of the same, independent, distribution. i.e. it always holds (via the Wald's equation) that

$$\frac{R}{E(\Delta_i)} \le \frac{E(h)}{h_{opt}} \le \frac{R}{E(\Delta_i)} + \frac{1}{h_{opt}} \quad \Rightarrow \quad E(C_h) \simeq \frac{R}{E(\Delta_i)} = \frac{1}{E(\cos\alpha_i)} \tag{1}$$

for large $h$. To understand the power of this, let us assume that the search phase always returns *two points* $p''$, $p'''$ each uniform in $(-\alpha, \alpha)$ and that the protocol selects the best of the two points, with respect to the local (vertical) progress.

Let $\alpha_{i1}$, $\alpha_{i2}$ the angles of the particles found and let $\alpha_i = \min\{|\alpha_{i1}|, |\alpha_{i2}|\}$. Then, for any $0 \le \phi \le \alpha$, it is:

$$\mathbb{P}\{\alpha_i > \phi\} = \mathbb{P}\{|\alpha_{i1}| > \phi \cap |\alpha_{i2}| > \phi\} = \left(\frac{2\alpha - 2\phi}{2\alpha}\right)^2 = \left(\frac{\alpha - \phi}{\alpha}\right)^2$$

Thus, the distribution function of $\alpha_i$, for any $0 \le \phi \le \alpha$, is

$$F_{\alpha_i}(\phi) = \mathbb{P}\{\alpha_i \le \phi\} = 1 - \frac{(\alpha - \phi)^2}{\alpha^2} = \frac{2\alpha\phi - \phi^2}{\alpha^2}$$

and the probability density function is, for any $0 \le \phi \le \alpha$:

$$f_{\alpha_i}(\phi) = \frac{d}{d\phi}\mathbb{P}\{\alpha_i \le \phi\} = \frac{2}{\alpha}\left(1 - \frac{\phi}{\alpha}\right)$$

The expected local progress is:

$$E(\cos\alpha_i) = \int_0^\alpha \cos\phi\, f_{\alpha_i}(\phi)\, d\phi = \frac{2}{\alpha}\int_0^\alpha \cos\phi\, d\phi - \frac{2}{\alpha^2}\int_0^\alpha \cos\phi \cdot \phi\, d\phi \tag{2}$$

Let $A = \int_0^\alpha \cos\phi \cdot \phi\, d\phi$. Then

$$A = \sin\phi \cdot \phi|_0^\alpha - \int_0^\alpha \sin\phi \cdot 1\, d\phi = \alpha \cdot \sin\alpha + \cos\alpha - 1 \tag{3}$$

Then from (2),(3)

$$E(\cos \alpha_i) \;=\; \frac{2}{\alpha} \cdot \sin \alpha \;-\; \frac{2}{\alpha^2} \cdot A \;=\; \frac{2(1-\cos \alpha)}{\alpha^2}$$

**Lemma 5.1** *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* $h$*.*

We remark that

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

Also it is:

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

Thus we get:

**Lemma 5.2** *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* $0 \leq \alpha \leq \frac{\pi}{2}$*.*

We remark that, w.r.t. 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 $(\pi/2 - \pi^2/8)/(\pi/2) \simeq 21.5\%$. We plan to study the further gain of additional (i.e. $m > 2$) searches.

# 6 Tight upper bounds to the hops distribution of the general target protocol

Consider the particle $p$ (which senses the crucial event) at distance $x$ from the wall. Let us assume that when $p$ searches in the sector $S$ defined by angles $(-\alpha, \alpha)$ and radius $R$, another particle $p'$ is returned *in the sector* with some probability density $f(\vec{p'})d\mathcal{A}$, where $\vec{p'} = (x_{p'}, y_{p'})$ is the position of $p'$ in $S$ and $d\mathcal{A}$ is an infinitesimal area around $p'$.

**Definition 6.1** *(Horizontal progress)* Let $\Delta x$ be the projection of the line segment $(p, p')$ on the line from $p$ vertical to $\mathcal{W}$.

We assume that each search phase returns such a particle, with independent and identical distribution $f()$.

**Definition 6.2** *(Probability of significant progress)* Let $m > 0$ be the least integer such that $\mathbb{P}\{\Delta x > \frac{R}{m}\} \geq p$, where $0 < p < 1$ is a given constant.

**Lemma 6.1** For each continuous density $f()$ on the sector $S$ and for any constant $p$, there is always an $m > 0$ as above.

**Proof:** Remark that $f()$ defines a density function $\tilde{f}()$ on $(0, R]$ which is also continuous. Let $\tilde{F}()$ its distribution function. Then we want $1 - \tilde{F}(R/m) \geq p$ i.e. to find the first $m$ such that $1 - p \geq \tilde{F}(R/m)$. Such an $m$ always exists since $\tilde{F}$ is continuous in $[0, 1]$. ∎

**Definition 6.3** Consider the (discrete) stochastic process $P$ in which with probability $p$ the horizontal progress is $R/m$ and with probability $q$ it is zero, where $q = 1 - p$.

**Definition 6.4** Let $Q$ the actual stochastic process of the horizontal progress implied by $f()$.

**Lemma 6.2** Let $Q$ the actual stochastic process of the horizontal progress implied by $f()$. Then $\mathbb{P}_P\{h \leq h_0\} \leq \mathbb{P}_Q\{h \leq h_0\}$

**Proof:** The actual process $Q$ makes always more progress than $P$. ■

Now let $t = \left\lceil \frac{x}{R/m} \right\rceil = \lceil \frac{mx}{R} \rceil$. Consider the integer random variable $H$ such that $\mathbb{P}\{H = i\} = q^i(1-q)$ for any $i \geq 0$. Then $H$ is geometrically distributed. Let $H_1, \ldots, H_t$ be $t$ random variables, independent and identically distributed according to $H$. Clearly then:

**Lemma 6.3** $\mathbb{P}_\mathrm{P}\{$*the number of hops is* $\mathrm{h}\} = \mathbb{P}\{\mathrm{H}_1 + \cdots \mathrm{H}_\mathrm{t} = \mathrm{h}\}$

The probability generating function of $H$ is

$$H(s) = \mathbb{P}\{H = 0\} + \mathbb{P}\{H = 1\}s + \cdots + \mathbb{P}\{H = i\}s^i + \cdots$$

i.e.

$$H(s) = p(1 + qs + q^2s^2 + \cdots + q^is^i + \cdots) \;=\; \frac{p}{1 - qs}$$

But the probability generating function of $\sum_t = H_1 + \cdots + H_t$ is then just $\left(\frac{p}{1-qs}\right)^t$ by the convolution theorem of generating functions. This is just the generating function of the $t-$fold convolution of geometric random variables, and it is *exactly* the distribution of the *negative binomial distribution* (see [7], Vol. I. p. 253). Thus,

**Theorem 6.4** $\mathbb{P}_P\{\text{the number of hops is } h\} = \binom{-t}{h}p^t(-q)^h = \binom{t+h-1}{h}p^tq^h$

**Corollary 6.5** For the process $P$, the mean and variance of the number of hops are:

$$E(h) = \frac{tq}{p} \qquad Var(h) = \frac{tq}{p^2}$$

**Discussion:** Note that the method sketched above, finds a distribution that upper bounds the number of hops till the crucial event is reported to the wall. Since for all $f()$ it is $h \geq \frac{x}{R} = h_{opt}$ we get that

$$\frac{E_P(h)}{h_{opt}} \leq \frac{\lceil \frac{mx}{R} \rceil \frac{q}{p}}{x/R} \leq \frac{(m+1)q}{p}$$

**Theorem 6.6** The above upper bound process $P$ estimates the expected number of hops to the wall with a guaranteed efficiency ratio $\frac{(m+1)(1-p)}{p}$ at most.

**Example:** When for $p = 0.5$ we have $m = 2$ and the efficiency ratio is 3 i.e. the overestimate is 3 times the optimal number of hops.

## 7 The "RETRY" Protocol

In the analysis of the previous two protocols, we have made the simplifying assumptions that the search phase for a target takes zero time and each hop (data transmission) to the target takes a constant time $t$. Under such assumptions, the hops efficiency and the time efficiency coincide. Also, under these assumptions, the "min two targets" protocols always outperforms the "local target protocol" with respect to both time and number of hops needed.

Consider now the more general (and possibly more realistic) case where the search phase takes time $t_s$ and the data transmission takes time $t_{tr}$. The new conditions give rise to a third protocol: As in the local target protocol, the particle that received *info($\mathcal{E}$)* initially searches for a particle nearer to $\mathcal{W}$ than itself. Then, however, it does not necessarily transmit data to that particle immediately. Instead, it decides with some probability (that can be optimized) to perform one more search and then transmit the data to the best (w.r.t. local vertical progress) of the two particles found.

Clearly the second search incurs an extra search time $t_s$, in hope of finding a better (w.r.t. to distance) particle. It is clear that retrying always benefits distance (and thus the number of hops and thus energy consumption too), however the effect of retries in time efficiency may be negative. On the other hand, avoiding retries may lead to short propagation time but at the same time may increase the number of hops.

Thus, in the new protocol, which we call the "RETRY" protocol, the time efficiency and the energy consumption (number of hops) *interplay*. In the sequel, we give an analysis indicating how to find an optimal trade-off between the two parameters. In particular, we will estimate the probability according to which a retry should be attempted in order to minimize time efficiency while keeping the number of hops at an acceptable level provided by the protocol implementer.

Recall that $h$ is the number of hops needed to reach the wall. Clearly, $h$ is a random variable. To guarantee the time efficiency constraint, we want

$$E(h) \ = E(h_1) + E(h_2) \ \leq \ h_{qos} \qquad \text{(IN1)}$$

where $h_{qos}$ is a kind of quality of service specification provided by the protocol implementer. Clearly have

$$E(h_1) \geq 0 \ \ , \ \ E(h_2) \geq 0 \qquad \text{(IN2),(IN3)}$$

where $h_1$, $h_2$ be the number of no retries and retries, respectively. By linearity of expectation, Wald's equation and by using the results on the local progress of the local target and the min-two uniform targets protocols, we have

$$\frac{\sin\alpha}{\alpha} E(h_1) \ + \ \frac{2(1-\cos\alpha)}{\alpha^2} E(h_2) \simeq B \qquad \text{(IN4), (IN5)}$$

where B is $d(p, \mathcal{W})$. We remark that, in fact, a careful application of Wald's equation leads to two inequalities (the one corresponding to the stopping time where the transmitted data gets within transmission range of the wall and the other corresponding to the stopping time where data have been received by the wall).

Furthermore, the expected total time of the RETRY protocol is, by linearity of expectation,

$$E(T_{tot}) \ = \ (t_s \ + \ t_{tr}) \cdot E(h_1) \ + \ (2t_s \ + \ t_{tr}) \cdot E(h_2) \tag{4}$$

Thus, in order to get the minimum $E(T_{tot})$ value we have to solve the following Linear Program:

```
   min E(Ttot)
when
for i=1 to 5
INi holds
```

The unknowns here are $E(h_1), E(h_2)$. Any polynomial time LP algorithm can be used.

## 8 The "SLEEP-AWAKE" Protocol

Because of the extremely restricted power supplies of smart-dust systems, each grain particle may alternate between sleeping and awake modes in order to save power. During sleeping periods grain particles cease any communication with the environment, thus they are unable to listen, receive and propagate data transmitted by other particles. However, the sleeping particles are able to sense any changes in their environment and thus are able to wake upon sensing a crucial event (see [8]).

Propagation protocols for such energy-restricted systems should at least guarantee that the wall *eventually* receives the messages that report a crucial event. The success of such protocols depends on the density $d$ of grain particles per $m^2$ and their distribution, the distribution of sleeping and awake time periods and, of course, on the angle $\alpha$ of the search beacon.

We below provide some first results on the interplay between these parameters. In particular, we focus on the relation between the maximum sleeping time period and the other parameters, thus allowing to program the smart-cloud energy saving specifications accordingly.

To simplify the analysis we assume that the grain particles are uniformly distributed on the smart-dust plane. Thus, in the area inspected during a search phase of beacon angle $\alpha$ between $R$ and $R + \Delta R$, the number of grain particles is

$$N = d \cdot \left( \frac{\alpha}{\pi} \pi (R + \Delta R)^2 - \frac{\alpha}{\pi} \pi R^2 \right) \simeq \alpha (2\Delta R + \Delta R^2) d \simeq 2\alpha \Delta R d$$

Now, we assume that the sleeping/awake time periods alternate independently in each particle and have lengths $s$, $w$ respectively (this can be easily achieved if during the start-up phase, the first awake period $w$ is set using a random bit generator, or is hardcoded into the particle by the manufacturer). Thus, the probability that at least one of the $N$ particles in the sender's beacon search area is awake is:

$$P_1 \;=\; \mathbb{P}\{\textit{at least one particle is awake}\} \;=\; 1 \;-\; \left( \frac{s}{s+w} \right)^N \;=\; 1 \;-\; \left( \frac{s}{s+w} \right)^{2\alpha \Delta R d}$$

Thus the probability that the event report eventually reaches the wall is:

$$P(success) \;=\; \sum_{h_0=1}^{\infty} P_1^h \; \mathbb{P}\{h = h_0\}$$

where $\mathbb{P}\{h = h_0\}$ is the probability density function of the random variable $h$.

Let now $\beta = \frac{s}{w}$ i.e. $\beta$ represents the energy saving specifications of the smart dust particles (a typical value for $\beta$ may be 100). Then,

$$r = \frac{s}{s+w} = 1 - \frac{1}{1+\beta}$$

By taking $d$ such that $2\alpha\Delta R d \simeq n(1+\beta)$ we get $P_1 = 1 - e^{-n}$. Then, by the Bernoulli inequality, we have $P_1^{E(h)} \geq 1 - E(h)e^{-n}$. This probability is non-zero when

$$n > \ln E(h)$$

This final condition allows to set the technical specifications and the propagation time accordingly in order to guarantee that the crucial event is eventually reported to the wall.

# 9 Conclusions and Future Work

We presented here a model for Smart Dust and a few basic protocols (and their average case analysis) for local detection and propagation. We are currently working towards the design of local protocols than can monitor the spreading of a time-sequence of events (i.e. tracking protocols).

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# Appendix

## A Technological Specifications of Smart Dust Devices.

Each smart dust device has a size on the order of a cubic inch which contains the four basic subsystems: power, computation, sensors and communication.

One of the tightest constraints on the circuit design is the operating voltage. Since the device operates using batteries, and because the RF chip sets in the design require a very narrow operating range centered at `3 Volts`, [8] focuses on `3V` portable power sources (in particular Lithium batteries that operate at the desired voltage, with `285 mWatt-hrs/gram` energy density and `10mA` max current at `10.5 grams`).

To operate for long periods of time, the grain particles are designed to enter sleep mode in order to save power. During this period, virtually all microprocessors on the market can go into low power modes that consume about 1$\mu$W (on average).

Taking into consideration the computational needs of the system, [8] uses an `8 bit` microcontroller (Amter AVR AT90LS8538) that provides a minimum of `1.25 MIPS/mA`, at an operating voltage of `2.7-5.5V` with `4K` flash memory. An alternative to this is the `16/32 bit` Strong Thumb processor (Amter AT91M404000) that provides `0.6 MIPS/mA`, but operates at `2.7-3.6V` and offers external memory capabilities.

Sensors provide the raw data the grain particles need to gain a high level understanding of the environment. The sensors themselves can be classified into two

groups: (1) weather monitors, and (2) motion detectors. [8] uses a magnetometer, accelerometer, light sensor, temperature sensor, pressure sensor and humidity sensor. All sensors consume 200-650$\mu$A and operate at a voltage range of `2.7-9V`.

Finally, regarding the communication subsystem, we will report three different technologies. The TR1000 RF Monolithis transceiver is designed for short-range wireless data applications, consumes an average of `18 mWatts` of power, and provides bit rates up to `19.2kbps` at distances of `5-30m`. The Bluetooth compliant Philstar PH2401 transceiver chip consumes less than `20mA` of power with throughput of `1 Mbit/s` at distances of up to `10m`. Finally, an alternative to RF communication is the one-way asynchronous laser communication which consumes `50mA` of power and provides bit rate up to `5kbps` at distances of `21.4km`.

It is worth noting that currently, a number of research institutions in the U.S. are working on centimeter-scale distributed sensor networks [2, 11].