Evaluation of basic protocols for optical smart dust networks*

Josep Díaz, Jordi Petit, and Maria Serna

Departament de Llenguatges i Sistemes Informàtics
Universitat Politècnica de Catalunya
Jordi Girona Salgado 1–3
08034 Barcelona
{diaz,jpetit,mjserna}@lsi.upc.es

Abstract. In this paper we analyze empirically the performance of several protocols for a random model of sensor networks that communicate through optical links. We provide experimental evidence of the basic parameters and of the performance of the distributed protocols described and analyzed under assymptotic assumptions in [3] for relatively small random networks (1000 to 15000 sensors).

1 Introduction

The fast development of microelectronics and communications has opened a fast field in the development of low-cost, little power consumption and small size, multi-functional sensors. Large number of these sensors can be spread to form *networks of sensors* [1]. Sensor networks are supposed to be deployed in hostile environments, in order to permit monitoring and tracking of remote objects, detecting anomalous situations as fires in the woods, seismic activity, and others. Communication among the sensors is usually done by radio frequency or, in more recent projects, by optical transmission via small lasers (see i.e. [4, 5, 8]). Free-space optical links have the limitation of an uninterrupted line-of-sight path for communication, but avoid radio interference. In particular, the Smart Dust project at Berkeley [6, 8] has proposed the use of optical communication between sensors as an alternative to radio frequency. Both in the case of radio frequency and of optical communication, the energy consumption is a key factor in the evaluation of these networks.

Recent efforts have been made to formalize and to give more efficient algorithms for networks of sensors, but these efforts have mainly concentrated on models using radio frequency communication [2, 7]. In [3], the authors proposed a probabilistic model to analyze smart dust networks communicating through optical devices. Although simple, our model seems to incorporate the basic technological specifications of smart dust systems [5]. We also considered and analyzed there some basic communication protocols in the proposed model, taking

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into account power management as a main issue in their design. Such protocols represent a research challenge, due to the optical nature of these networks and because of the presence of faulty connections among sensors. However, the analytical results obtained in [3] were mostly of asymptotic nature. In the present work, we experimentally study whether these asymptotic results hold for smaller networks.

Recall that the setting of smart dust systems is to have a *base-station transceiver* (BTS) at a relative elevation (or in a small plane) monitoring periodically the information of a large amount of sensors (*motes*) that have been scattered on a terrain. Motes include sensor devices, a small laser cannon and a set of optical devices able to modulate and reflect the light they receive. Fig. 1 reproduces the design of such a mote.

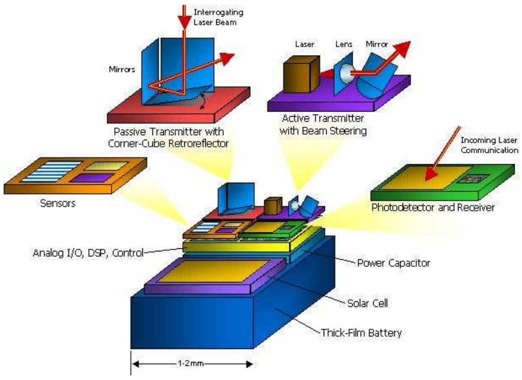

Fig. 1. Elements in the motes of the Smart Dust project (reproduced from [5]).

The scenario considered in [3] is as follows. The motes are scattered massively at random from a vehicle. As a consequence some of them may break or fall in such a way that can not communicate with the BTS. Then, the communication will be initiated from the BTS: the BTS scans an area with its laser, and each mote passively modulates and reflects the beam. This is the preferred way to communicate, as the mote uses little power. If a mote is shadowed from the BTS, this mote must rely its information to the BTS through other motes (any mote can detect a failure of communication with the BTS by noticing that sufficient time has passed without communication). Communication between motes is done in an active way using their laser beams. This kind of transmission uses more power. To send information, they use an orientable low power laser beam, which current technology allows to move sidewards and upward about forty degrees. To receive information, motes have an optical device able to detect and interpret laser signals, as well as to evaluate the direction of the incoming beam.

The network is established in two phases. The *localization* phase consists in finding out the position of each mote; that is, at the end of this phase it is required that all operative motes know their approximate coordinates (GPS systems cannot be currently used because of their volume, price and power consumption). The second phase consists in establishing a route from the motes that cannot communicate directly with the BTS through the motes than can. Such phase is called *route establishment* and is attained by repeated operations of broadcasting and gathering protocols. Once these two main steps are performed, the network is able to enter in its exploitation phase, which will last until the power supply of the motes decays.

In this paper, we give empirical evidence that the system and protocols described and analyzed in [3] perform correctly, with only a small increase in the predicted constants, when dealing with networks of a few thousand sensors.

2 The model

In this section, we recall the random model for smart dust systems that was proposed in [3].

According to [3], we deal with an ideal two dimensional squared region in which a mote falls with coordinates following the uniform distribution. Any mote can orient its laser cannon in any position of its scanning area, which covers a sector of a fixed angle of α radians. The sector is also oriented randomly with an angle b relative to some horizon, but the mote can receive light from any point, within distance r, which is "looking" to it. We assume that the terrain to be covered is an square area of size $D \times D$. An appropriate scaling can map it to the unit square $[0, 1]^2$.

These considerations give raise to a directed graph model. We define a random digraph, where the vertices are the motes, and given vertices i and j, there is an arc (i, j) if j lies in the sector with center i defined by r, starting at angle α and ending at angle $\alpha + b_i$ (modulo 2π). More specifically, let $X = (X_i)_{i\geq 1}$ be a sequence of *independently and uniformly distributed* (i.u.d.) random points in $[0, 1]^2$, let $B = (b_i)_{i\geq 1}$ be a sequence of i.u.d angles and let $(r_i)_{i\geq 1}$ be a sequence of numbers in $[0, 1]$. For any natural n, we write $\chi_n = \{X_1, \ldots , X_n\}$ and $\beta_n = \{b_1, \ldots , b_n\}$. We call $\mathcal{G}_\alpha(\chi_n, \beta_n, r_n)$ the *random scaled sector graph* with n nodes.

The objective of the network is monitoring the terrain. To do so, we assume that the terrain is dissected in a grid of s cells, each of size $s^{-1/2} \times s^{-1/2}$. This grid serves as reference position for the motes, and the data reported from a mote refers to the cell in the grid that contains it. The parameter s is selected to represent the *sensing precision* of the network and controls its scalability.

In the process of scattering the motes, some of them may break down or fall upside down and become inoperative, some may be hidden from the BTS and for some pair of motes the line of sight may be blocked. We assume that motes fall uniformly at random in the terrain and that each mote can fail, independently at random, with probability $1 - p_o$. Operative motes communicate with the BTS with probability p_b. Also, we assume that p_c is the probability that the line of sight allowing communication from one operative mote to another operative mote is not interrupted by any obstacle.

We use the following parameters to describe a *smart dust network*: n is the number of motes; r is the laser range of the motes; α is the laser scanning angle; s is the number of cells in the grid; p_o is the probability that a mote is operative; p_b is the probability that an operative mote can communicate with the BTS (these are called *communicating motes*); p_c is the probability that the line of sight between two motes is not interrupted. We consider here that p_o, p_c and p_b are fixed probabilities.

As defined in [3], the *random smart dust network* $\mathcal{SD}_n(X, B, \alpha, r, s, p_o, p_b, p_c)$ is a network of n motes $X_1, \dots, X_n$ where X_i is operative with probability p_o, X_i can communicate with the BTS with probability p_b, and X_i and X_j can communicate with probability p_c if X_j is contained in the sector of radius r and angle α starting at β_i. In the remaining of the paper, such system will be simply denoted as $\mathcal{SD}_n$.

We will use the term *ϵ-normalized random smart dust system* to refer to a random smart dust system $\mathcal{SD}_n$, with $n = (1+\epsilon)(s \ln s)/p_o$ motes and such that $g = r/\sqrt{s}$ is a constant and $\epsilon \geq \epsilon_0$. Here, ϵ_0 is a constant that depends on g. This selection of n is made according to [3], where it is stated that, with high probability, a random smart dust system with n motes can effectively monitor s cells. Given the laser range r and the number of cells s, the value $g = r/\sqrt{s}$ is another relevant parameter that will appear in the analysis of random smart dust systems. In our experiments we take $g = 10$.

Most of the results relate to *interior motes*, defined as those motes whose distance to the boundaries of $[0, 1]^2$ is greater than r.

3 Connectivity

It is known that, with high probability, the interior motes of normalized smart dust systems are strongly connected:

Theorem 1 ([3]). *Let $\mathcal{SD}_n$ be a ϵ-normalized smart dust system. Then, w.h.p., for all pairs (x, y) of interior operative motes, there is a directed path from x to y.*

Recall that a sequence of events $(E_n)_{n \geq 0}$ occurs *with high probability (w.h.p.)*, if $\lim_{n\to\infty} \mathbf{Pr}[E_n] = 1$. As a consequence, the result in the above theorem is just asymptotic and does not provide any clue on how fast the probability converges to 1. Our first set of experiments provides an analysis of the network connectivity. The goal is to simulate smart dust networks in order to know whether the predicted asymptotic behavior holds in small networks for different values of its parameters.

To do so, we have generated different random networks with $\alpha = 40$ degrees and have measured the number of interior motes that belong to the largest strongly connected component for different values of n, p_o and p_c. The number of motes (n) has been selected in the range 1000 to 15000 with increments of 1000; we believe that this is a reasonable number of motes. The probability of communication between motes (p_c) has been selected in the range 0 to 1, with increments of 0.1, in order to cover a wide spectrum of possibilities. In this and all the following experiments, we have taken $r_n = \log n/\sqrt{n}$ for the radius; the rationale behind this selection is that the results in [3] hold for $r_n > c_0\sqrt{(\log n)/n}$ for c_0 large enough, and our selection is just slightly greater than any c_0. In all the experiments, we have also restricted the values for the probability of being operative (p_o): We have selected three different values: 0.15, 0.5 and 0.85; these represent low, medium and high probabilities.

The obtained results are presented in Table 1, which shows the percentage of interior motes that belong to the largest strongly connected component related to the total number of interior motes. The experiments have been repeated 200 times, without noticing large deviations from the averages, which are shown in the tables.

As it could be expected, the results show that as n, p_c or p_o grow, the ratio of number of motes in the largest strongly connected component grows. More importantly, the results show that for certain values of the parameters, almost 100% of the pairs of interior motes are connected. This shows that the asymptotic predicted behavior in Theorem 1 can be observed even for relatively small values of the n, p_c and p_o parameters.

4 The localization algorithm

Once deployed, the first task for a smart dust network is to find the position of each operative interior mote. Motes that can communicate with the BTS will receive its coordinates from it (it suffices to include the emission angle in the BTS message [5]). The remaining motes will have to compute their coordinates based on the coordinates of other motes and the angle of incidence of the incoming laser beams. In this section, we simulate the localization algorithm localize proposed in [3] to solve the localization stage for optical smart dust systems. We refer to [3] for a complete description of this protocol. The expected performance and runtime of the localize protocol is given by the following result:

Theorem 2 ([3]). *Let $\mathcal{SD}_n$ be an ϵ-normalized random smart dust system. Then, as s grows, w.h.p., after a constant number of phases of the localize protocol, all operative interior motes know their position.*

Again, the result is asymptotic. Moreover, the required number of steps is unknown. Therefore, our goal in this section is two-fold: we want to know whether the localization phase can be performed with the localize algorithm when the number of motes is in the order of a few thousands, and we want to know how many phases are needed.

In this case, the probability p_b of reaching the BTS matters. Therefore, the parameters for these simulations involve n, p_b, p_o and p_c. Again, we take $p_b \in \{0.15, 0.50, 0.85\}$. Tables 2, 3 and 4 show the empirical results obtained using the localize protocol. From these values, it can be observed that the localization phase will succeed when p_c, p_b or p_o are high, but that for a low number of motes and a low values of p_c, p_b or p_o the algorithms fails to assign coordinates to each interior operative mote. In theses cases, though, more than 90% of the interior motes could compute their position. With regards to the number of phases needed to complete the algorithm, our results indicate that, in the average, 6 phases are enough and that never more than 20 phases have been required.

5 Broadcasting from the BTS to the motes

Another of the issues to be considered is the broadcasting of messages originated in the BTS. We consider the simple-bro protocol given in [3], which is a classical flooding algorithm with multiple source points. The theoretical analysis of the broadcasting protocol in the random smart dust network is the following:

Theorem 3 ([3]). *Let $\mathcal{SD}_n$ be an ϵ-normalized random smart dust system. Then, as s grows, w.h.p., after performing $4\lceil\sqrt{2p_o/(p_b(1+\epsilon)g^2)}\rceil$ phases of the simple-bro protocol, a message originated in the* BTS *will be broadcasted to all interior motes.*

Using the same parameters as in the experiments done in the previous section, Tables 5, 6 and 7 show the percentage of interior motes which receive the message transmitted by the BTS using the simple-bro protocol, within the number of phases indicated in Theorem 3. Again, for reasonable values of p_o and p_b, we can observe that as n and p_c grow, the percentage of interior motes receiving the message originated in the BTS in the prescribed number of phases soon goes over 95%.

6 Route establishment from the motes to the BTS

Before exploiting the network of sensors, a smart dust system must establish a routing so that any operative interior mote can send its information to the BTS. Motes that can communicate directly with the BTS will simply transmit passively their information when the BTS queries them. The remaining motes will have to send their information actively by the way of multiple hops. Since the communication between motes is not bidirectional, we can not simply reverse the paths found by the previous algorithm.

To establish a route from the mote to the BTS, we use the protocol simple-link described in [3]. That protocol computes a set of the routes from the motes to the BTS form an oriented forest with roots in the communicating motes.

Theorem 4 ([3]). *Let $\mathcal{SD}_n$ be an ϵ-normalized random smart dust system. Then, as s grows, w.h.p., after performing $4/\left\lceil\sqrt{(p_o p_b g)}\right\rceil$ phases of the simple-link protocol, all interior motes have selected a neighbour to whom send the information to be forwarded to thr* BTS.

The important part in the analysis of the previous algorithm done in [3] was the fact that, asymptotically, almost all pairs of motes at Euclidean distance less than r are at distance at most 4 in the network. Therefore, in this case, our experiments focus on this property rather than in the whole simulation of the simple-link protocol. Using the same parameters as in the previous experiments, Tables 8 and 9 present the measured results. (Unfortunately, we could not compute shortest paths in networks with more than 5000 motes when $p_o = 0.85$.) In any case, these show that for the smaller number of nodes that we are dealing with the number of phases of broadcasting used in each simple-link phase must be increased to 6.

7 Conclusions

In this paper, we have investigated whether the asymptotic results we draw in [3] hold for normalized smart dust systems with thousands of motes.

Our experiments have focussed on the simulation of the basic protocols presented in [3] and span several basic tasks to exploit networks of sensors. The parameters we have used to study our protocols are the size of the network (n) and the different failure probabilities (p_o, p_c and p_b). We have reported results for $\alpha = 40^o$, but simulations with $\alpha = 20^o$ present a similar behavior.

The results we have reported show that the predicted asymptotic behavior can be detected on small networks by setting the probabilities to reasonably high values, at the expense of a slight increase of the constants. Observe that this increase of the constants only delays the length of the broadcasting, but does not result in any additional increment of energy consumption that remains as one full scan per mote and per phase of the simple-link protocol.

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$p_o = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	2	2	3	4	9	17	23	29	43	52
3000	0	1	2	7	20	40	61	72	81	88
5000	0	1	3	9	31	59	70	87	89	92
7000	0	0	2	12	45	71	83	90	94	95
9000	0	0	3	27	64	77	85	91	94	97
11000	0	0	4	32	68	82	88	92	95	97
13000	0	0	5	32	70	83	90	94	96	98
15000	0	0	7	43	72	84	91	94	97	98

$p_o = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	1	27	77	90	96	98	99	99	99	99
3000	2	69	91	97	99	99	99	100	100	100
5000	5	78	95	98	99	99	99	100	100	100
7000	12	83	96	99	99	99	100	100	100	100
9000	20	86	97	99	99	100	100	100	100	100
11000	29	87	97	99	99	100	100	100	100	100
13000	35	89	98	99	99	100	100	100	100	100
15000	37	90	98	99	99	100	100	100	100	100

$p_o = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	1	27	77	90	96	98	99	99	99	99
3000	2	69	91	97	99	99	99	100	100	100
5000	5	78	95	98	99	99	99	100	100	100
7000	12	83	96	99	99	99	100	100	100	100
9000	20	86	97	99	99	100	100	100	100	100
11000	29	87	97	99	99	100	100	100	100	100
13000	35	89	98	99	99	100	100	100	100	100
15000	37	90	98	99	99	100	100	100	100	100

Table 1. Percentage of interior motes that belong to the largest strongly connected component.

$p_o = 0.15$, $p_b = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	16	14	15	20	14	28	20	23	59	52
3000	14	16	16	24	56	63	73	82	77	94
5000	15	15	30	40	72	80	92	93	95	97
7000	15	20	43	43	82	88	85	96	97	98
9000	14	19	40	76	86	90	95	96	98	98
11000	15	21	52	71	87	92	95	97	98	98
13000	15	28	48	79	88	92	96	97	98	99
15000	16	22	59	81	89	94	96	97	98	99

$p_o = 0.5$, $p_b = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	14	37	75	88	98	99	99	100	100	100
3000	35	87	96	99	99	99	100	100	100	100
5000	54	91	97	99	99	100	100	100	100	100
7000	64	93	98	99	99	100	100	100	100	100
9000	66	94	98	99	99	100	100	100	100	100
11000	69	95	99	99	100	100	100	100	100	100
13000	71	95	99	99	100	100	100	100	100	100
15000	74	96	99	99	100	100	100	100	100	100

$p_o = 0815$, $p_b = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	39	94	98	99	99	100	100	100	100	100
3000	81	97	99	100	100	100	100	100	100	100
5000	86	98	99	100	100	100	100	100	100	100
7000	89	99	99	100	100	100	100	100	100	100
9000	90	99	100	100	100	100	100	100	100	100
11000	91	99	100	100	100	100	100	100	100	100
13000	92	99	100	100	100	100	100	100	100	100
15000	93	99	100	100	100	100	100	100	100	100

Table 2. Percentage of interior motes that get their coordinates after 20 steps.

$p_o = 0.15$, $p_b = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	51	52	55	64	80	80	85	87	83	93
3000	52	55	74	79	88	92	94	95	97	97
5000	51	70	78	87	91	94	95	96	97	98
7000	55	73	80	86	93	94	96	98	98	99
9000	58	73	81	88	93	95	97	97	99	99
11000	59	74	84	90	93	96	97	98	99	99
13000	58	75	84	90	94	96	98	98	99	99
15000	61	76	85	91	94	96	98	98	99	99

$p_o = 0.5$, $p_b = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	64	87	95	97	99	99	99	99	99	100
3000	79	93	97	99	99	99	99	100	100	100
5000	82	95	98	99	99	100	100	100	100	100
7000	84	96	99	99	99	100	100	100	100	100
9000	84	97	99	99	100	100	100	100	100	100
11000	85	97	99	99	100	100	100	100	100	100
13000	87	97	99	99	100	100	100	100	100	100
15000	87	97	99	99	100	100	100	100	100	100

$p_o = 0.85$, $p_b = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	85	96	99	99	100	100	100	100	100	100
3000	91	98	99	100	100	100	100	100	100	100
5000	93	99	99	100	100	100	100	100	100	100
7000	94	99	100	100	100	100	100	100	100	100
9000	95	99	100	100	100	100	100	100	100	100
11000	95	99	100	100	100	100	100	100	100	100
13000	96	99	100	100	100	100	100	100	100	100
15000	96	99	100	100	100	100	100	100	100	100

Table 3. Percentage of interior motes that get their coordinates after 20 steps.

$p_o = 0.15$, $p_b = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	86	84	87	86	92	94	97	98	97	97
3000	85	86	93	95	96	97	98	98	99	99
5000	86	91	94	97	97	98	98	99	99	99
7000	87	91	95	96	97	98	99	99	99	99
9000	88	92	95	97	98	98	99	99	99	99
11000	89	93	95	97	98	99	99	99	99	99
13000	89	93	96	97	98	99	99	99	99	99
15000	90	94	96	97	98	99	99	99	99	99

$p_o = 0.5$,$p_b = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	90	96	98	99	99	99	99	99	100	100
3000	94	98	99	99	100	100	100	100	100	100
5000	95	98	99	99	100	100	100	100	100	100
7000	95	99	99	100	100	100	100	100	100	100
9000	96	99	99	100	100	100	100	100	100	100
11000	96	99	99	100	100	100	100	100	100	100
13000	96	99	99	100	100	100	100	100	100	100
15000	96	99	99	100	100	100	100	100	100	100

$p_o = 0.85$, $p_b = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	95	99	99	99	100	100	100	100	100	100
3000	97	99	99	100	100	100	100	100	100	100
5000	98	99	100	100	100	100	100	100	100	100
7000	98	99	100	100	100	100	100	100	100	100
9000	98	99	100	100	100	100	100	100	100	100
11000	98	99	100	100	100	100	100	100	100	100
13000	98	99	100	100	100	100	100	100	100	100
15000	99	99	100	100	100	100	100	100	100	100

Table 4. Percentage of interior motes that get their coordinates after 20 steps.

$p_o = 0.15$, $p_b = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	18	27	30	33	36	48	44	59	67	73
3000	20	28	33	41	46	59	63	71	74	82
5000	20	27	39	45	54	63	70	76	81	84
7000	22	30	40	49	58	66	74	78	85	87
9000	22	31	43	53	61	72	78	82	85	90
11000	22	32	43	53	64	71	80	84	88	90
13000	23	33	45	56	65	74	80	83	89	91
15000	23	35	45	56	66	74	82	86	90	93

$p_o = 0.5$, $p_b = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	28	49	61	85	90	92	97	98	99	99
3000	37	62	83	92	96	98	99	99	99	100
5000	41	71	88	95	98	99	99	100	100	100
7000	43	72	89	96	99	99	99	100	100	100
9000	44	75	90	97	99	99	100	100	100	100
11000	48	78	92	98	99	99	100	100	100	100
13000	49	79	93	98	99	99	100	100	100	100
15000	50	81	94	98	99	99	100	100	100	100

$p_o = 0.85$, $p_b = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	45	74	89	98	99	99	100	100	100	100
3000	55	87	97	99	100	100	100	100	100	100
5000	62	91	98	99	100	100	100	100	100	100
7000	67	93	99	99	100	100	100	100	100	100
9000	69	95	99	100	100	100	100	100	100	100
11000	70	95	99	100	100	100	100	100	100	100
13000	72	96	99	100	100	100	100	100	100	100
15000	73	97	99	100	100	100	100	100	100	100

Table 5. Percentage of interior that receive a message from the BTS.

$p_o = 0.15$, $p_b = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	57	65	71	72	82	81	87	90	92	93
3000	59	68	75	81	87	89	92	94	95	97
5000	60	69	76	84	87	92	94	96	97	97
7000	60	71	79	85	89	93	95	96	98	99
9000	62	72	79	87	91	94	96	97	98	99
11000	62	72	81	88	91	94	96	98	99	99
13000	62	74	82	89	92	95	97	98	98	99
15000	62	73	83	89	93	96	97	98	99	99

$p_o = 0.5$, $p_b = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	66	77	84	91	92	95	97	97	98	99
3000	70	84	90	94	97	98	98	99	99	99
5000	73	85	92	96	97	98	99	99	99	99
7000	74	87	93	96	98	99	99	99	99	100
9000	75	88	94	97	98	99	99	99	99	100
11000	76	89	94	97	98	99	99	99	99	100
13000	76	89	94	97	99	99	99	99	100	100
15000	78	90	95	98	99	99	99	99	100	100

$p_o = 0.85$, $p_b = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	73	87	94	97	98	99	99	99	100	99
3000	80	93	97	98	99	99	100	100	100	100
5000	82	94	98	99	99	99	100	100	100	100
7000	84	95	98	99	99	100	100	100	100	100
9000	85	95	98	99	99	100	100	100	100	100
11000	85	96	98	99	99	100	100	100	100	100
13000	86	96	99	99	99	100	100	100	100	100
15000	87	96	99	99	100	100	100	100	100	100

Table 6. Percentage of interior that receive a message from the BTS.

$p_o = 0.15$, $p_b = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	85	89	93	96	92	95	97	98	98	98
3000	89	91	94	95	97	97	98	98	99	99
5000	89	92	95	96	97	98	98	99	99	99
7000	89	93	96	96	98	98	99	99	99	99
9000	89	93	95	97	98	98	99	99	99	99
11000	90	93	96	97	98	99	99	99	99	99
13000	90	93	96	97	98	99	99	99	99	99
15000	90	93	96	97	98	99	99	99	99	99

$p_o = 0.5$,$p_b = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	93	95	98	99	99	99	99	100	99	100
3000	94	97	99	99	99	100	100	100	100	100
5000	94	98	99	99	99	100	100	100	100	100
7000	95	98	99	99	99	100	100	100	100	100
9000	95	98	99	99	100	100	100	100	100	100
11000	96	98	99	99	100	100	100	100	100	100
13000	95	99	99	99	100	100	100	100	100	100
15000	96	99	99	99	100	100	100	100	100	100

$p_o = 0.85$, $p_b = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	95	98	99	99	100	100	100	100	100	100
3000	96	99	99	100	100	100	100	100	100	100
5000	97	99	99	100	100	100	100	100	100	100
7000	98	99	100	100	100	100	100	100	100	100
9000	98	99	100	100	100	100	100	100	100	100
11000	98	99	100	100	100	100	100	100	100	100
13000	98	99	100	100	100	100	100	100	100	100
15000	98	99	100	100	100	100	100	100	100	100

Table 7. Percentage of interior that receive a message from the BTS.

$p_o = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	1	3	5	9	17	22	33	36	40	50
3000	1	3	8	16	25	37	52	60	70	78
5000	1	4	10	19	33	47	56	70	78	82
7000	1	4	11	20	37	57	65	75	83	88
9000	1	4	11	24	39	57	67	79	84	91
11000	1	5	12	26	43	60	71	82	87	92
13000	1	5	13	28	47	63	75	84	90	94
15000	1	5	14	30	49	65	78	86	91	94

$p_o = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	2	12	44	73	88	95	98	99	99	100
3000	3	30	74	93	98	99	99	100	100	100
5000	4	41	82	96	99	99	100	100	100	100
7000	5	46	87	98	99	99	100	100	100	100
9000	6	53	91	98	99	100	100	100	100	100
11000	7	57	93	99	99	100	100	100	100	100
13000	7	62	94	99	99	100	100	100	100	100
15000	8	65	95	99	99	100	100	100	100	100

$p_o = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	5	51	89	98	99	100	100	100	100	100
3000	13	80	98	99	100	100	100	100	100	100
5000	19	88	99	100	100	100	100	100	100	100
7000	24	93	99	100	100	100	100	100	100	100
9000	27	95	99	100	100	100	100	100	100	100

Table 8. Percentage of pairs of interior motes that are at Euclidean distance $\leq r$ and their graph distance is ≤ 4.

$p_o = 0.15$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	1	3	5	8	13	21	26	31	32	43
3000	1	3	7	13	20	28	36	44	52	60
5000	1	4	8	16	22	30	42	50	57	66
7000	1	4	8	15	24	36	45	55	63	72
9000	1	4	9	17	26	37	49	59	67	74
11000	1	4	10	19	28	40	52	61	68	75
13000	1	4	10	18	29	41	52	65	72	78
15000	1	5	10	20	31	43	54	65	73	79

$p_o = 0.5$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	2	9	22	45	63	78	85	93	96	97
3000	2	15	38	63	82	91	96	98	99	99
5000	3	18	46	72	88	94	98	99	99	99
7000	3	21	51	77	91	96	98	99	99	100
9000	4	23	55	80	92	97	99	99	99	100
11000	4	25	58	83	93	98	99	99	99	100
13000	4	26	61	84	94	98	99	99	100	100
15000	4	28	63	86	95	98	99	99	100	100

$p_o = 0.85$, $\alpha = 40^o$

n	p_c									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1000	3	22	51	79	91	96	98	99	99	100
3000	6	37	76	92	98	99	99	100	100	100
5000	7	46	83	96	99	99	100	100	100	100
7000	9	52	87	97	99	99	100	100	100	100
9000	10	55	89	98	99	100	100	100	100	100

Table 9. Percentage of pairs of interior motes that are at Euclidean distance $\leq r$ and their graph distance is ≤ 6.