

# Investigating the “Wireless Wire”

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## Introduction

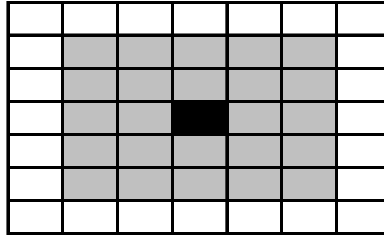
Advancements of silicon technology have led to the field of Micromachining in which it is now possible to create discrete transmitting and receiving devices on the scale of a cubic millimeter. Given such technological capabilities, it is now worth while investigating situations in which these devices can be utilized. In this paper a network of such devices is considered for the end task of propogating information from one point to another without physical interconnections, but rather a series of signal transmission amongst the devices we refer to as “mikroDust”. Possible applications may include communication across a battlefield, with Unmanned Vehicles spreading the dust, or in an area where other means of communication have broken down, e.g. after an earthquake.

Message propagation across a virgin mikroDust field demands the field meet a filling fraction to allow for connectedness across the system. Percolation theory sets this requirement for filling fraction (or probability of site occupation), and is referred to as the percolation threshold. Above this threshold, the system possesses a connected cluster of mikroDust particles spanning the entire system and providing a pathway for a message to be propagated across the field. Below the percolation threshold, a connected cluster no longer spans the field, and successful message transmission is no longer possible.

In our model, the percolation field is composed of mikroDust modules which are probabilistic repeaters with finite energy reservoirs. Each module receives an incoming signal and, with a probability set by the states of its neighbors, it re-transmits the signal. As each mikroDust module exhausts its energy reservoir, the filling fraction of the percolation field decreases. Using simple strategies, an optimal approach to extending the lifetime of the percolation field is studied.

## Description of a Model

The field of mikroDust is modeled as a two dimensional 15 by 30 grid. The density of the dust is controlled by changing the probability that each square contains a mikroDust. Each device has a transmission distance of two squares. Figure 1 illustrates the transmission range (grey) of the transmitting square (black):



**Figure 1. Transmission range of 1 particle**

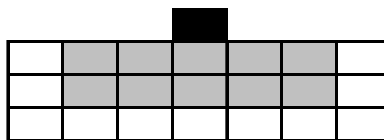
The probability that any given mikroDust particle will transmit a message at the  $n$ th time step is a function of the number of number of transmissions it received at time  $n-1$  ( $\#received$ ):

$$P_{transmit} = \begin{cases} 1 - \alpha(\#received) & \#received > 0 \\ 0 & \#received = 0 \end{cases} \quad (1)$$

In this equation,  $\alpha$  represents a “laziness” factor added to increase the lifetime of the system. If a mikroDust receives more copies of a message, it is less likely to transmit a message, since it will be more likely that other mikroDust also received the message and will transmit. By not transmitting, the mikroDust saves energy, but on the other hand creates a probability that the message propagation through the entire network will fail .

In order to prevent the back propagation of signals, after a mikroDust transmit a message, it enters a refractory period for several time steps. During this period, the mikroDust is not capable of receiving messages. Further in order to model the limited power of the small transmitters, each particle is only capable of transmitting a fixed number of messages. After using all of its transmissions, it is “dead”, i.e. behaves like an empty grid cell.

In order to start the message, the transmitter which is located at the center of the short edge of the grid transmits three copies of the message as shown in Figure 2. The transmitter is represented in black and its transmission range is shown in grey.



**Figure 2. Start of Message**

## Results

### Robustness and Back Propagation of Signal

The importance of adding a long enough refractor period can easily seen by running the model with a small refractory period of 2 (Figure 3). The message initially travels forward, but because of the short refractory period, a mikroDust behind the message flow retransmits the message backward, producing a rapid backward spread of the signal. This problem can be easily eliminated by increasing the refractory period, as shown in Figure 4.

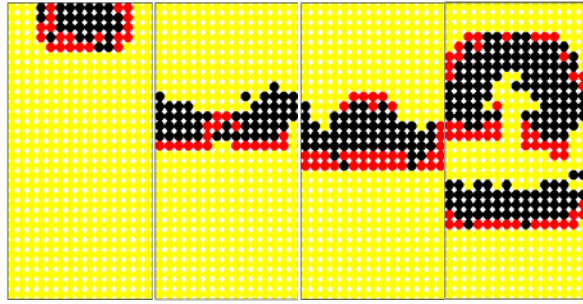


Figure 3. Backpropagation of signal

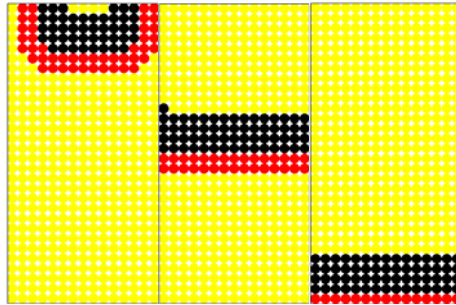


Figure 4. Successful transmission with longer refractory period

### Variation of $\alpha$

In order to study the effects of changing  $\alpha$ , its value was varied over a range from 0 to 0.3, assuming a density of 1, and a lifetime of 5 transmissions for each particle. During each test, the transmitter sent continuous messages until messages could no longer be sent since too many particles died. Fifty tests were run, and the number of successfully received messages were recorded. The results, show how the use of the “laziness” factor is able to greatly increase the overall lifetime of the system (Figure 5). If the “laziness” is too great ( $>$  than about 0.3), however, no messages are able to propagate.

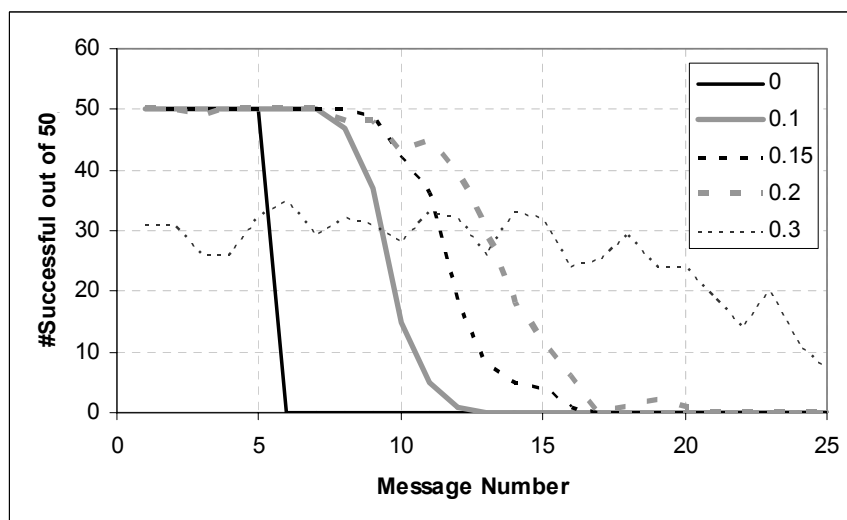


Figure 5. Changing alpha with density = 1  
(probability of firing =  $1 - \alpha * (\text{\#messages received})$ )

### Variation of density of particles

In order to explore the effects of varying the density of particles, another set of tests was performed. The  $\alpha$  “laziness” factor was fixed at .15 and each mikroDust again had a lifetime of 5 transmissions. The density of the particles was varied. Figure 6 illustrates the overall trend that decreasing the density of the particles reduces the performance of the system. An interesting fact can be observed for densities near 0.9, however, which appears to have better performance than a density of 1. These nonintuitive results can be possibly be explained by the transmission rules in Equation (1). A higher density of particles increases the chance that a particle will receive more copies of a message. Since it receives more copies, it will have a lower probability of transmitting the message, increasing the chances that the overall transmission of the message will fail.

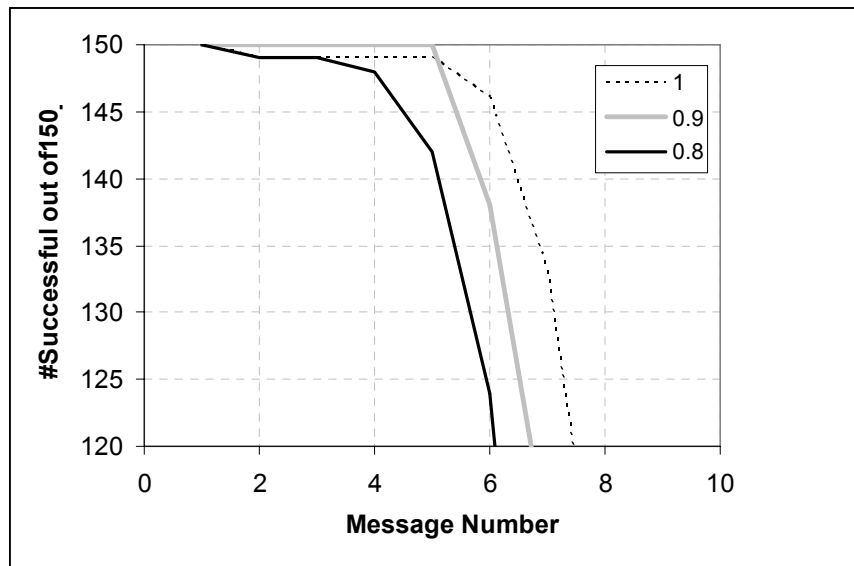


Figure 6. Changing density with alpha = .15

### Requiring Message Redundancy

One possible problem with the transmission rule in Equation (1) is that if a mikroDust malfunctions and sends an erroneous message, this message can be retransmitted throughout the array. In order to prevent this, the rule can be modified:

$$P_{\text{transmit}} = \begin{cases} 1 - \alpha(\# \text{received} - 1) & \# \text{received} > 1 \\ 0 & \# \text{received} \leq 1 \end{cases} \quad (2)$$

This modified version of the rule requires that at least two copies of a message must be received in order to retransmit the message. Thus a single mikroDust sending a rogue message cannot propagate the message. The system was tested for various values of  $\alpha$  for a density of 1. The results, shown in Figure 7, illustrate that this modified rule reduce the performance of the system. This reduction in performance illustrates a probable tradeoff between robustness to malfunctioning particles and system performance, although different strategies could produce both high levels of performance and robustness.

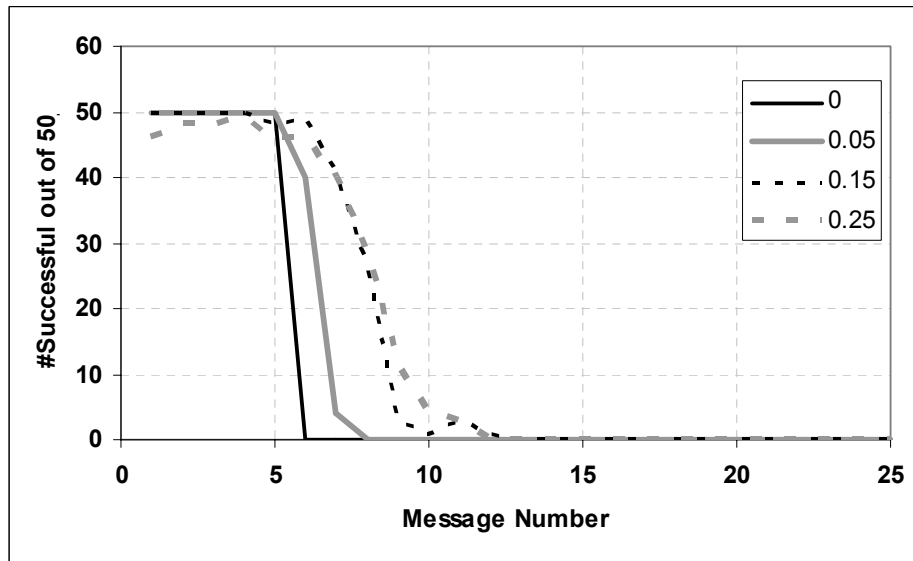


Figure 7. Changing alpha with density = 1  
(probability of firing =  $1 - \alpha * (\text{\#messages received} - 1)$ )

## Discussion

We studied the effect of different parameters on the performance of a simple model of mikroDust. Perhaps one of the most interesting findings is that the lifetime of the system can be doubled by including a 'laziness-factor'  $\alpha$ . This may be important for real-world use, given that the energy budget of a mikroDust particle will always be greatly constrained by its size.

The phenomenon of backpropagation is common to many models of excitable media. One example with considerable importance to everyday life is the causation of cardiac dysrhythmias, resulting from irregularities in the heart tissue (Figure 8).

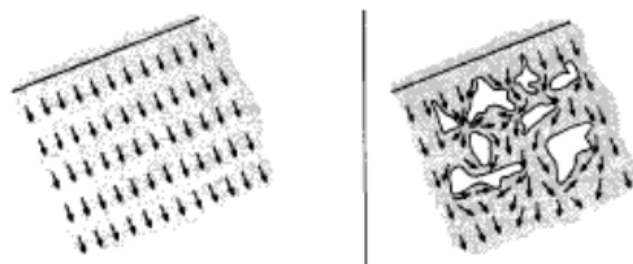


Figure 8: model of wave propagation on undisturbed (left) and disturbed (right) heart tissue. After Smith and Cohen (1984)

More elaborate applications of the concepts developed in this paper apply to miniature distributed networks for cellphone towers in urban areas as well as communication between sensor networks. Such applications require consideration of the most optimal frequency bandwidth for transmission as well as the method of linking the devices for optimal robustness and energy efficiency. Strategies detailed in current literature discuss using discrete mirrors to bounce signals from one discrete component to another, thus optimization of the angles of the mirrors becomes another topic. Needless to say there are

many possible factors and possible applications to consider in the future development of miniature distributed networks.

Clearly, there are many more factors that may influence the behaviour of the model, such as a non-uniform distribution of the particles due to wind. Also, various combinations of the described parameters might yield behaviours that we did not observe so far. To examine the model systematically, however, was beyond the scope of this study. Still we believe that it is a valid approach to the problem, and that our findings give some insight into the problem.

## Literature

Franceschetti (2002): Percolation model for urban area propagation: results and open problems. *IEEE*

Hsu, V.S., Kahn, Pister (1998): Wireless Communications for Smart Dust, *Electronics Research Laboratory Memorandum Number M98/2*

Smith, J M, Cohen, R J (1984): Simple finite-element model accounts for wide range of cardiac dysrhythmias. *Proc. Natl. Acad. Sci.*, **81**, 233 – 237.

Warneke, B, Last, M, Liebowitz, B, Pister, K S J (2001): Smart Dust: Communicating with a Cubic-Millimeter Computer. *IEEE Computer*, **34**, 44 – 51.

*For more information of Classical Percolation Theory:*

Stauffer, D, Aharony, A (1992): *Introduction to Percolation Theory*, 2<sup>nd</sup> ed. Taylor and Francis, London.