Reconvening after a Break in Communication

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Abstract - Mobile ad hoc networks and software-defined radio provide new ways of reconvening after a break in communication caused by an emergency. We show that the structures formed by the rally point heuristics we describe are related to diffusion-limited aggregates. Using this result, a model is developed for estimating the time to reconvene given region width, number of units, and radio coverage.

1. Introduction

In large-scale emergencies, communication tends to break down. Power grids may be knocked out, which in turn may silence transmitters. Dust may occlude radio communication. The communication infrastructure which survives may be flooded with traffic to the point where it becomes unusable. How can we reestablish communication between members of a team?

Teams can agree on a rally point ahead of time: if the team becomes separated, and can no longer communicate, team members are to reconvene at a designated point. Rally points are suggested in survival manuals [1], and are often a part of corporate disaster recovery plans.

Ad hoc radio networks change the nature of rally points. Units with ad hoc radio radios do not have to reconvene physically, but might stop moving at the point at which they connect to the rally point. Due to the transitive nature of ad hoc networks, the unit the furthest away from the rally point may only have to travel to the perimeter, rather than the center, of an aggregate.

Movement can serve communication [2, 3]. Previously, we claimed that the time to move into a position to communicate is a form of latency, and can be optimized [4, 5].

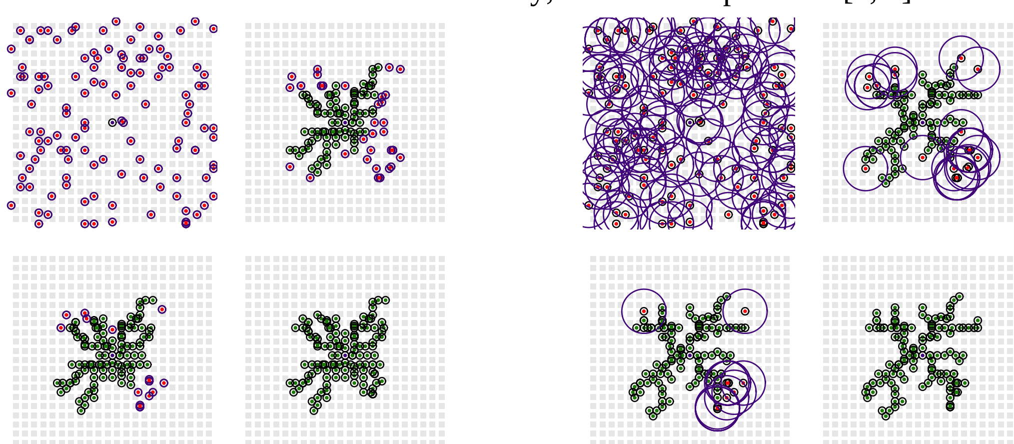

Figure 1. On the left, 1A, Frames from a simulation, left to right, top to bottom. The rally point is in the center of each frame (width of 111, density of .01, city grid of 5, radio range of 4). In 1A, the field converged in 55 time steps. In 1B, on the right, the blue circles represent an extended radio range. It converged in 49 time steps.

Our motivating research questions are: what simple rules might be used to reconvene disconnected parties possessing ad hoc network technology? For particular heuristics, what patterns are formed, and how quickly? Our goal is to build decision aids, so that response to emergencies can be planned ahead of time. Our work, then, is one step toward an emergency decision support system, and is related to other information systems research toward this goal [6-8], as well as to organizational research on coordination [9]. Next, we explain the heuristics.

2. HEURISTICS: SIMULATION RESULTS

Fig. 1A shows a series of frames from a simulation of our proposed heuristics. The inner solid circle represents the unit, and the outer circle indicates a communication radius. Units are shown in red when disconnected from the rally point, and are shown in green once connected. The units we simulate proceed directly toward the rally point. They are homogeneous: all the units (we simulate between 100 and 500) have the same capabilities and run the same program. They stop in place if they find themselves in radio contact with the rally point, either directly or through other units. This is the *ad hoc network heuristic*.

We also consider another heuristic, one in which a node moves toward the nearest connected node – that is, a node that is connected to the rally point, perhaps through a chain of other nodes. This is the *discovery heuristic,* shown in Fig. 1B. How might a unit know which is the nearest node that is connected into the network? It might be in line-of-sight (LOS) of the node. Alternatively, it might be able to use a smart or cognitive radio to discover the presence and the associated protocols of a weak signal: software-defined cognitive radios can change the transmitted waveform characteristics such as bandwidth and frequency [10]. A lower frequency will propagate further. Thus, a temporary reduction in frequency might be used as a way of transmitting and receiving short messages containing location information.

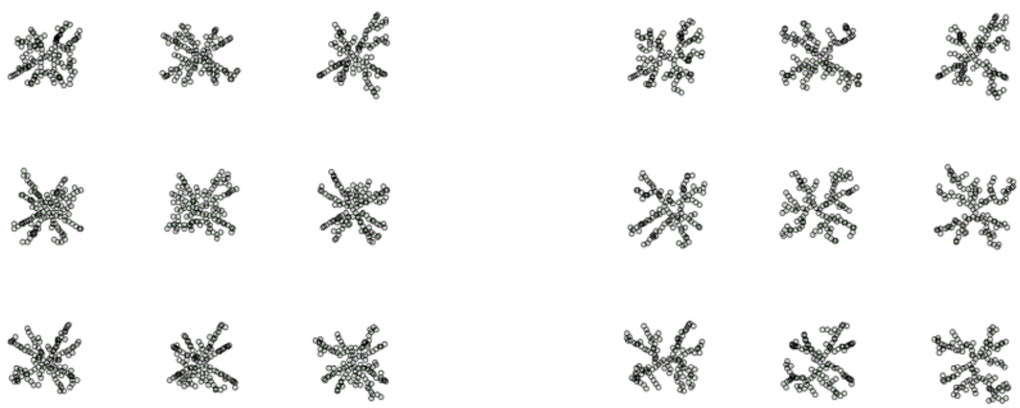

Figure 2. On the left, aggregates with the ad hoc network heuristic. The mean time to converge across these 9 trials was 38 time steps (Field width of 111, density of .01, coverage diameter of 4, no extended range). On the right, aggregates with the discovery heuristic (extended range 6x normal range). The mean time to converge across these 9 trials was 34 time units (Field width of 111, coverage diameter of 4, extended range of 24).

The time to reconvene is the time for all units to come together, which is the same as the time for the last team member to connect. We want to measure this maximum time for a given starting distribution – the shorter the time, the better for an emergency situation. We will study the effect several variables on the time to reconvene: the width of the area, the number of units, and the radio coverage. We are interested in the tradeoff between the component factors: we want to know whether it is better to increase radio coverage or add units. A single rally point is assumed; multiple connected rally points are considered in a sequel [11].

Fig. 2 shows the resulting configuration of 9 different runs, using first the ad hoc heuristic in 2A, and then the discovery heuristic in 2B.

3. The Model

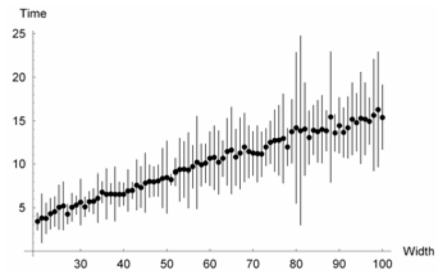

Figure 3. The time to reconnect (density of .05, coverage diameter of 4, no extended range)

We now seek to understand the relation between the different factors. Each point in Fig. 3 represents the mean result of running the algorithm on 20 random configurations. The error bars represent variance.

We find a linear relationship between the width of the starting field and the time to reconnect, assuming a constant density of units. Specifically, starting with a square field of a certain width, we allocated units at random, consistent with a given density. As the width increases, the time to reconnect increased linearly. This deserves explanation.

The configurations in Fig. 2 look like *diffusion-limited aggregates*. Research on these aggregates began with simulations done by Witten and Sander [12]. Witten and Sander describe a process in which a start particle is placed on a grid. Then other particles, moving at random, beginning from locations far away, will stick to the start particle upon collision. Later, other particles may stick to already aggregated particles. The discovery heuristic also has a physical analogy. Some natural processes will attract particles toward the closest part of the aggregate; for example, one study mentions electromigration transport in a cell [13].

Vicsek provides a set of equations which summarizes the physics research on diffusion-limited aggregates ([14], p. 140). Our conjecture is that the rally point behaviors we have described obey the same rules as diffusion-limited aggregates. This is plausible: our description of the patterns of units converging is virtually identical to that of particles converging.

We are most interested in the rate of growth of the perimeter, which the units are likely to intersect with. Since the structures form differently based on the initial distributions and since the pattern formed are axial in nature, the radius of gyration is often used as a measure of the structure:

$$R_g(n) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} r_i^2}$$

with r_i the distance to the center of mass, in this case the rally point. The fractal dimensionality D of the aggregate was shown by Meakin [15] to be related to the radius of gyration of the aggregate in the following way:

$$R_g(n) \sim n^{v}, \textit{where } v = 1/D \qquad (1)$$

The variable n represents the number of particles. In extensive simulations, diffusion limited aggregates have exhibited a dimensionality of about 1.71, and so v is about .585 [14]. In building our model, we can assume one of two scenarios: a fixed number of units that will have to work across different size spaces, or a variable number of units with constant density that work across different size spaces. The model, once built, can apply to either situation. For expositional purposes, we work through the later scenario.

Assuming a constant density of units, N will grow in proportion to the square of the area width w, so, from equation 1,

$$R_g(w^2) \sim w^{2v} \sim w^{2*.585} \sim w^{1.17} \quad (2)$$

In other words, as we increase the width of the area, the radius of gyration will grow in a roughly linear fashion.

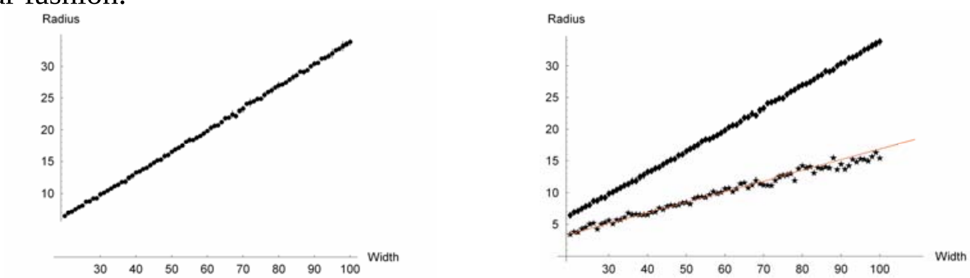

Figure 4. On the left, 4A, the radius of gyration, with error bars representing variance (the variance is small and the error bars hard to see). On the right, 4B, the radius of gyration (diamonds) and the time to reconnect (stars, with no variance shown). The red line shows a fit to equation (4).

Fig. 4A shows the radius of gyration for the same aggregate as in Fig. 3, each point representing the mean of 20 runs. From equation 1, a model for the radius of gyration is:

$$R_g = \frac{n^v}{b} \quad (3)$$

where b is a scaling constant.

With v =.5, the model is linear with respect to the width, and the model fits the simulation with the proportion of explained variation (r-squared) >.99. Even though the number of units is growing as the square of the width, the structure is building out as the square root of the number of units, a result of the fractal nature of the structure. Therefore we see a linear relationship.

As the radius of gyration grows in a roughly linear fashion, we expect that the amount of time for the units to reconvene will also grow in a roughly linear fashion, as the units are colliding with the growing aggregate. The two things are related; as each point collides with the structure, the structure grows.

When the rally point is in the center of the field, the time to connect is bounded by some fraction of the width, $\frac{w}{a}$. We can think of this as representing the unit furthest from the center in the starting distribution; given a high enough density, this will be a unit in one of the corners. The value of the constant a depends on the type of lattice being used; it will be 2 using the conventions of a square lattice where diagonal moves are allowed, 1 when diagonal moves are not allowed, as in constrained city grids, and $\sqrt{2}$ in off-lattice situations. Using equation 3, a heuristic for estimating the amount of time to converge is

$$t \approx \frac{w}{a} - \frac{n^v}{b} \quad (4)$$

where b is a constant factor, and v is a fractal dimension $\approx .5$.

In other words, the time to converge is the distance of the furthest point minus the expected radius of the structure it will converge into. Fig. 4B shows equation 4 applied; we fit the radius of gyration line. Then we effectively drop the slope of the line by $\frac{w}{2}$, yielding the gray line, which in turn fits the time line with an r-squared of .99. This data set is for a particular density; the same relationships hold for all lower and most higher densities of starting nodes. As the density gets very high, the connectivity of the nodes is nearly instantaneous, and the resulting structure resembles the starting random distribution.

Radio coverage is also a factor in the time to reconnect. From a set of starting units with coverage = *c*, an isomorphic set with coverage = 1 can be created with width $\frac{w}{c}$. The entire space is scaled downward. If this reduced set converges in time *t*, the original set will converge in time *t* * *c*.

So, substituting $\frac{w}{c}$ for w and scaling by *c* in (4), as well as setting $v = .5$ yields

$$t \approx \left(\frac{\frac{w}{c}}{a} - \frac{\sqrt{n}}{b} \right) c \approx \frac{w}{a} - \frac{c\sqrt{n}}{b} \qquad (5)$$

Intuitively, the arms of the aggregate are multiplied in length by *c*. This equation can be used to evaluate the tradeoff between increasing either the number of responders or the radio coverage.

Fig. 5A shows the effect of the discovery heuristic on the same 20 random starting configurations as in Fig. 3.

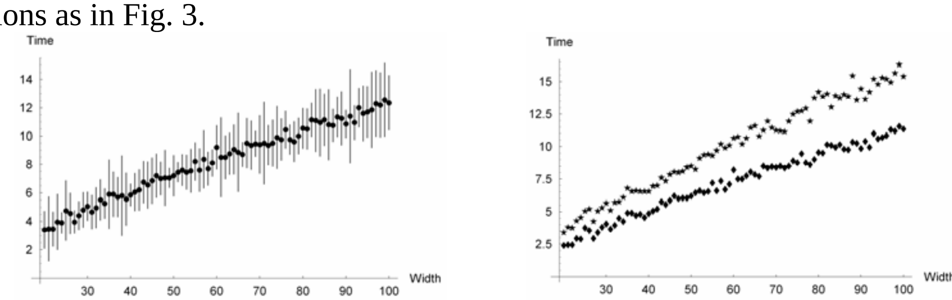

Figure 5. On the left, 5A, the time to reconnect using a heuristic that includes increased radio awareness. Error bars represent variance. (density of .05, coverage diameter of 4, extended range of 10). On the right, 5B, a comparison of the two heuristics, with the discover heuristic shown by diamonds.

The variance is reduced from the first heuristic, because the outlying units veer toward the closer perimeter nodes rather than continuing toward the center. The discovery heuristic gets comparatively better as the width increases. At width 100, the second heuristic is better by 35%. The heuristic is both faster and more predictable.

4. Conclusions

We examined ways of planning for the re-establishment of communication using rally points in conjunction with mobile ad hoc networks. Robots and humans alike might converge on rally points, stopping when they are connected. In this manner, communication may be reestablished relatively quickly. Thus, we have designed a form of systems integration, one that includes transportation in the service of communication. This is the theoretical contribution of our work.

The aggregates formed are similar to those found in nature. The previous analysis of such aggregates can inform our planning. Specifically, aggregates created from the heuristics described here can completely connect in an amount of time roughly linear in the diameter of the initial region for a given density of units.

There are also pragmatic implications. Consistent with the heuristics we described, responders can be given software-defined radios for use if their primary radio system fails, along with one piece of information: a rally point. The model we developed can be used to understand when responders will reconvene. The model can also be used to decide on the density of responders and the radio coverage necessary to achieve emergency response goals.

More generally, this work suggests that there may be new productive ways to use movement to establish wireless communication. Because human spatial behavior often exhibits a pattern of dispersion followed by consolidation, it is possible that there are more applications for these rally point heuristics in situations where movement and information are intertwined.

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REFERENCES

[1] DOD, "US Army Survival Manual: FM 21-76," US Department of Defense 1992.

[2] S. Alpern and S. Gal, *The theory of search games and rendezvous*. Boston: Kluwer, 2003.

[3] D. K. Goldenberg, J. Lin, A. S. Morse, B. E. Rosen, and Y. R. Yang, "Towards Mobility as a Network Control Primitive," *MobiHoc*, 2004.

[4] J. V. Nickerson, "Humans and Robots Reconvening," *IEEE International Conference on Systems, Man and Cybernetics*, 2004.

[5] J. V. Nickerson, "A Concept of Communication Distance and its Application to Six Situations in Mobile Environments," *IEEE Transactions on Mobile Computing*, vol. 4, pp. 409-419, 2005.

[6] M. Turoff, M. Chumer, B. V. d. Walle, and X. Yao, "The Design of a Dynamic Emergency Response Management Information Systems," *JITTA*, vol. 5, pp. 1-36, 2004.

[7] L. G. Mondschein, "The role of spatial information systems in environmental emergency management," *JASIS*, vol. 45, pp. 678 - 685, 1994.

[8] W. A. Schafer, J. M. Carroll, S. R. Haynes, and S. Abrams, "Emergency management as collaborative community work," *ECSCW*, 2005.

[9] R. Weber, "Managing growth to achieve efficient coordination in large groups," *American Economic Review*, vol. 96, pp. 114-126, 2006.

[10] J. Mitola, "The software radio architecture," *IEEE Communications Magazine*, vol. 33, pp. 26-38, 1995.

[11] J. V. Nickerson, "Assembling Sensor Networks," *HICSS*, 2007.

[12] T. A. Witten and L. M. Sander, "Diffusion-limited aggregation," *Phys. Rev. B*, vol. 27, pp. 5686, 1983.

[13] J. Erlebacher, P. C. Searson, and K. Sieradzki, "Computer Simulations of Dense-Branching Patterns," *Physical Review Letters*, vol. 71, pp. 3311-3314, 1993.

[14] T. Vicsek, *Fractal growth phenomena*, 2nd ed. New Jersey: World Scientific, 1992.

[15] P. Meakin, "Diffusion-controlled cluster formation in 2—6-dimensional space," *Phys. Rev. A*, vol. 26, pp. 1495-1507, 1983.