Task-based Self-Organization in Large Smart Spaces: Issues and Challenges[1]

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Abstract– Smart spaces of the future will consist of a large number of computing devices intelligently communicating with each other to perform various day-to-day tasks. Self-organization of these devices to form task-oriented clusters is a necessity as these devices grow in number. Given a rich collection of mobile tetherless smart-devices, it is important to investigate schemes for task-based self-organization so as to enable a large number of ubiquitous services and applications. We believe that making the self-organization process task-based, instead of depending on connectivity and nearness alone, will augment the richness of any given ad-hoc network of nodes and will enhance its capabilities significantly. We elaborate on some theoretical and practical research issues in task-based self-organization in this position statement.

[1] *Proc. DARPA/NIST/NSF Workshop on Research Issues in Smart Environments*, Georgia Intitute of Technology, Atlanta, GA, July 1999.

1 Introduction

Since wireless computing devices are rapidly shrinking in size and power consumption, they are becoming more *ubiquitous* and are contributing significantly in the realization of “smarter” environments. A *Smart Space* can be visualized as a collection of computing devices which *sense* the environment around them and then make certain actions happen accordingly. Since a smart space consists of several small and specialized devices, there is a strong need for networking them and thus make them act together towards a particular goal. For example, a light sensor can only sense the presence of light but it needs to send that information to an appropriate actuator so that the latter can trigger a particular event. Some of these requirements have been investigated in this position statement.

Imagine a smart living room with intelligent surround-sound speakers which are equipped with spread spectrum wireless transceivers. When their owner brings them home from the store and puts them on the floor, they bounce radio waves off the walls of the living room and off other appliances (both smart and dumb) therein, and judge the dimensions of the room. Then they exchange information between each other and instruct their owner to put them at certain places in the room for “optimum” sound-effects with respect to the smart couch in the room where the owner is most likely to sit and listen to music. After the owner places them where they want themselves to be placed, they track the listener’s movement and align (or rotate) themselves accordingly, continuously, assuming of course they have that freedom. Although this seems somewhat farfetched, smart environments are becoming a reality rapidly indeed.

Recently there have been quite a few attempts to build smart environments which include offices [7], homes [1], classrooms [3] and even play-spaces [5]. Although these environments have a gamut of specialized computing devices, they need a special physical infrastructure to co-exist and function together. We argue that a smart space can be setup rapidly in any scenario as long as the participating devices have the required capabilities. For instance, a dusty hall floor can be cleaned *smartly* if we release a number of small but smart vacuum-cleaner robots on the floor at night. These *vac-bots* (as we call them) do not need any existing physical infrastructure to work together. They have small attached brushes to collect the dust and small low-power vacuum cleaning devices to suck the dust. Also, they must have wheels to propel themselves and wireless links to communicate between each other. They will also have distance sensors to judge the dimensions of the hall and distribute the cleaning task efficiently among themselves. If some parts of the hall are dustier than the rest, then the vac-bots which were designated to clean those areas will summon other idle vac-bots to come to their help and finish the job quickly. We can easily see that these vac-bots can form an ad-hoc network among themselves and can self-organize to finish the task. They do not need any help from the existing infrastructure.

To make smart environments successful and easily deployable, the devices should be tetherless and self-configurable ("power-up-n-play" rather than "plug-n-play") and self-organizing. Each device should know its own capabilities and should communicate with other devices to perform higher order tasks. In the traditional sense, self-organization in ad-hoc networks refers to the formation of hierarchical clusters of nodes for the ease of routing and management [6]. We strongly feel that task-based self-organization (instead of plain connectivity- and nearness-based) in an ad-hoc network consisting of specialized devices significantly augments the capabilities of the network and also enhances the ease of its maintenance.

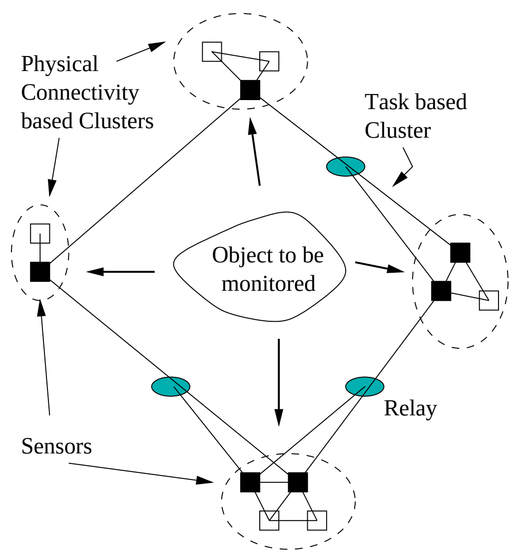

Figure 1: Task-based Self-Organization

Consider a network of sensors[2] distributed around a complex object as shown in Figure 1. The sensors, denoted by squares are supposed to sense the shape, position and motion of the object locally and then communicate between each other and perform certain computations on the global data set. The shaded ovals denote nodes which can relay packets between sensors. These nodes may be sensors themselves. Mere nearness based self-organization results in the clusters denoted by dashed ellipses. Although that helps in hierarchical routing and scalability, it provides little information and help to the particular task that the sensors are trying to perform. A task based cluster is denoted by dark squares (sensors) connected by solid lines via the shaded ovals (relays). We believe that a smart space will consist of

[2] Estrin et al. [4] describe such an application in detail

highly specialized devices (basically embedded systems) which can perform only a limited set of tasks rather than of full-fledged computers which can perform any computing job; hence it makes sense to organize them based on the task that a group of them is supposed to perform together, even though they may not be within a hop's distance from each other. That way, if unrelated devices happen to lie near each other, they will never try to form clusters together.

Once a task-based cluster, C is formed, it can advertise its services to the external world. Whenever a new device N joins the smart space, it can use the (first-order) services provided by the aforesaid cluster to perform a second order task. In that case a new task-based cluster comprising of the old cluster C and the new node N will be formed.

2 Research Issues and Challenges

The discussion in the previous section leads to several potential research issues:

- Each device has to somehow know its capability and should also know how it fits into the bigger scheme of things i.e. in the task. Schemes for efficient representation of the associations between devices (and also higher level clusters) have to be developed. A *task graph*, where nodes are devices (or clusters) and edges denote data flow between them, is one such simple representation.

- Once a task graph is available, algorithms for embedding it onto the physical ad-hoc network topology have to be devised. There may be quite a few candidate nodes but the algorithm must *discover* the best set of nodes from the lot which can perform the specified task. Tree based solutions in the discovery phase may not be good since they tend to increase the load on the intermediate nodes and links. The problem of optimally embedding an arbitrary task graph onto an arbitrary network of nodes is NP-hard [2], so heuristic solutions need to be found for specific situations.

- Protocols for formation of self-organizing clusters need to be developed. These may or may not be built on top of existing ad-hoc routing protocols. In fact we do not rule out their deployment on top of connectivity-based physical clustering techniques as described in [6]. The issues that need to be addressed while developing these protocols are means of exchanging state between devices and existing clusters, messaging overhead, frequency of state updates, effect of mobility of devices on the volatility of clusters, measures for quality of task-based clusters (e.g. diameter, dilation, load, link congestion) etc. Another important issue is to choose between leader election and leaderless clustering. Homogeneity or heterogeneity of devices may pose different challenges during protocol design.

- Addressing and routing within each cluster may be different from the existing schemes for hierarchical clustering. Conflict resolution during the discovery phase (e.g. if two smart-displays in a smart office want to participate in a presentation) is a key issue. Conflict-free naming of the clusters also has to be achieved.

- Scalability of clusters: When a new device joins the smart space and wants to participate in a task, the space should be easily augmented without much re-computation. Protocols for advertising services provided by existing clusters for the formation of higher-order task-based clusters need to be developed.

- Self-healing techniques: if some device fails, some other device has to take over the tasks of the failed device. Imagine a battalion of troops spread out over a certain battlefield. Each soldier has a device (maybe equipped with sensors) which is a part of one huge task-based cluster. If one soldier goes out of range or his device fails, then some other soldier's device must somehow perform the sub-tasks that were assigned to the former. Schemes for gracefully degrading the service while a new node is being brought into the cluster have to be developed.

- Power conserving algorithms may be needed to minimize the average power consumption of the devices trying to solve a particular task. e.g. if a node is not being used for sometime, it can go into slumber mode or even switch itself off.

For large clusters, the state information that needs to be maintained at various levels (connectivity, addressing and routing, sub-task mapping) is enormous. The smart elements are likely to be low-power and battery operated devices. Hence maintenance of higher-order state in a mobile ad-hoc network of such devices is clearly a major challenge.

Another major challenge in this entire endeavor is to make this whole process of self-organization transparent to the user. Since every user may have a large number of these devices capable of performing specialized tasks, their configuration should be entirely automatic, and without undesirable results. For example, in a smart office with smart printers, a situation where six pages in a ten page document are printed on printer A and the rest are printed on B, should not be allowed to happen.

3 Conclusions

In this paper, we have presented a case for task-based self-organization in an ad-hoc network of mobile smart devices. We discussed the potential benefits that task-based self-organization could offer and some issues (both theoretical and practical) and challenges involved in realizing the same. We also talked about some specific scenarios where these techniques could be useful.

References

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