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The Emergence MAC (E-MAC) protocol for wireless sensor networks

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ABSTRACT

Large scale biological systems often exhibit emergent properties that are attractive in an engineering context. In this paper, the context is a class of wireless sensor networks for emergency environmental monitoring. The attractive properties are simplicity, self-organisation, adaptiveness to scenario change and a lack of scenario-specific parameter tunings. Emergence Medium Access Control (E-MAC) is a scheme inspired by biological social populations that individually react to environmental stimuli. Using a very simple protocol, it exhibits the desired emergent properties. When compared to a well established practical counterpart, the IEEE 802.11 CSMA/CA standard, it exhibits better throughput, end-to-end delay and fairness. This paper describes the motivation and design of E-MAC, and presents the above comparison.

1. Introduction

Imagine the scenario where an emergency service, such as Fire and Rescue, is required to monitor a large area of moorland for spontaneous outbreaks of brush fire (Maltby et al., 1990). Any such monitoring would be required to report on temperature and humidity levels that indicate high risk conditions and, subsequently, the movement of fire fronts. The movement of fire fronts can be highly unpredictable and poses a serious danger to personnel and equipment. This is an ideal opportunity to deploy a wireless sensor network (WSN) over a wide area from a suitable aerial platform. Based on the operational need it is also possible to deploy more of these low-cost nodes.

This scenario presents a set of significant challenges (Sha et al., 2006). Long-term remote operation necessitates low power usage and a very simple MAC protocol in each inexpensive node. In contrast, nodes are required to minimise end-to-end delay with no sensor node being dominant (high fairness levels). In the case of these simple nodes, only one communications channel will be available, necessitating an efficient MAC protocol to control the transmissions, ensure correct operation and achieve high throughput. Nodes will be required, at different times, to act purely as relay nodes whilst at other times, they may be additionally required to generate and place data on the network. The protocol must facilitate adaptability.

Many protocols have been proposed for WSNs which offer different benefits (Du et al., 2007; Van Dam and Langendoen, 2003; Demirkol et al., 2006). Schemes that employ sophisticated synchronisation or significant information exchange to achieve organisation and performance are inappropriate in the context presented here. Yet, as the scale of networks increases, the need for some form of synchronisation and information exchange becomes overwhelming even if only at a local level.

Routing becomes a challenging task in large-scale networks as well. Dissemination of routing information and discovery of routes becomes difficult process. There are, however, many examples and proposals for good routing practices in the scientific community (Li et al., 2011; Al-Karaki and Kamal, 2004). In this paper we focus on the MAC layer.

Here, we present our proposed solution, Emergence Medium Access Control (E-MAC), and compare its performance to that of a basic implementation of the IEEE 802.11 standard. We choose this latter protocol because it is well understood and well established. Even though it uses some hardware capabilities such as carrier sensing and additional RTS/CTS messages, the IEEE 802.11 protocol itself is very simple and clean. We focus on comparative performances over a multi-hop chain. The contributions of E-MAC are:

- A different approach to MAC. The nodes search for the throughput they are able to achieve and then use this information for data transmissions/generation, regulating traffic flow.
- A very simplistic MAC protocol that allows nodes to achieve high throughput through multi-hop networks under a variety of situations without the need to tune system parameters.
- The proposed protocol also shows several emergent behaviours:
  1. self-organisation;
  2. flow control on both hop-by-hop and end-to-end basis;
  3. indirect synchronisation between the nodes as packets are relayed;

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4. minimal latency.

The structure of this paper is as follows: Section 2 outlines the biological inspiration for the E-MAC protocol. We then describe the protocol itself in Section 3. Section 4 presents the scenario and simulation parameters for the comparative performance. The results are described in Section 5.

2. Biological metaphors

The ability of natural systems to self-organise, reorganise and provide fault-tolerant operation has inspired a huge diversity of mathematical and engineering solutions (Tero et al., 2010; Mármol and Pérez, 2011; Kulkarni and Venayagamoorthy, 2010). For example, the evolutionary metaphor (e.g. genetic algorithms and genetic programming) has enabled otherwise intractable optimisations and facilitated the discovery of novel processes, algorithms and systems (Espejo et al., 2010). Similarly, the social metaphor (e.g. particle and robotic swarms and multi-agent systems) has done the same, and contributed to the understanding of the emergent properties of complex systems (Poli et al., 2007).

E-MAC was inspired by the social metaphor.

In this case, very simple entities, generally referred to as *agents*, can offer significant benefits and highly complex behaviours when operating in groups and interacting with each other using simple rules. This *swarming* offers emergent behaviour on a higher social level (Garnier et al., 2007). Examples from nature include:

- locust swarms which can fly in perfect synchrony in their billions, efficiently exploiting localised air streams (Camhi et al., 1995);
- ant colonies which exhibit complex foraging and task allocation behaviour without central coordination (Dorigo et al., 2000);
- termite colonies that can build complex structures without a global blueprint (Bonabeau, 1998).

All of these are achieved without central control, and only through very simple rules, interactions and reaction to the local agent environment, and without explicit encoding of the emergent behaviours. In each case there are up to millions of very simple entities that are continuously changing without affecting the overall performance. The complex behaviours arise from the interactions between individuals affecting their local environment. Self-organisation, adaptation and fault-tolerance are frequently the emergent properties of these systems. This simplicity and the same emergent properties correspond to what could be defined as ideal for WSNs.

When monitoring harsh environments over large areas of undulating terrain, we require cheap, simple nodes that can adapt to different communication scenarios without the need to tune specific system parameters. Also, network fault-tolerance is needed where nodes are likely to progressively fail at the onset of a fire front. Furthermore, adding nodes should not trigger wholesale network reconfiguration to accommodate them; only locally affected regions should adapt without affecting global emergent behaviour.

All of this *can* be otherwise achieved with precise deployment planning and complex algorithms. Such approaches tend to introduce many tunable parameters which require more operational maintenance. Also, it is not usually possible to anticipate every scenario and its conditions. We assert that it is better exploit biological metaphors that offer appropriate emergent properties through simple rules of interaction.

The E-MAC protocol employs the notion of reaction to the intensity of stimulus from neighbouring agents. We use a stochastic approximation of the probability of successful message packet transmission as that stimulus.

2.1. Task allocation and division of labour in social insects

Here we represent an example of stimulus-based self-organising emergent behaviour to illustrate our motivation for the development of the E-MAC scheme.

It has been observed that many species of social insects exhibit emergent task allocation and division of labour (Bonabeau et al., 1997). Without the need for a leader, colonies comprising huge number of individuals are able to organise their various tasks. The process usually arises through emergence from simple actions taken by individuals. In addition, such processes are highly robust and adapt to the different needs of the colony.

Bonabeau et al. (1999) proposed a model based on a response threshold that models the behaviour of ants and bees and shows emergence behaviour at the colony level for task allocation. The response threshold defines how individuals react to their environment (stimulus). It provides a way to define a probability of taking an action, given certain stimuli from environment and its relationship with the threshold of that stimulus. A threshold can be varied among different individuals – therefore creating specialised workers. For example, in an ant colony we can consider forager and fighter ants. Foragers will have a lower threshold for collecting food and a higher threshold for fighting. Therefore they will more likely take up foraging. Fighter ants with a reversed threshold would show a higher tendency towards fighting. Nevertheless given the lack of foragers, the stimuli for foraging increases, therefore fighter ants would start to get involved into foraging tasks as well. The process also involves a learning process. If an agent is performing a task, the threshold for that task will decrease (increasing the likelihood of performing that task again). This also provides a natural process for specialisation.

For example the probability to take up a task given a certain threshold and stimuli can be expressed as:

$$T_\theta(s) = \frac{s^n}{s^n + \theta} \tag{1}$$

where s is the environmental stimuli, θ the response threshold and n defines the steepness of the curve (see Fig. 1).

θ essentially defines the tendency to take up action given the environmental stimuli, so differently specialised insects would have different threshold towards certain tasks. For example, when θ is 1 in Fig. 1 the stimuli has to be very high to increase the probability of performing the task defined by this threshold. However, when θ is 50, even a small stimuli will have high probability of eliciting a response.

Another example (Fig. 2) of a response curve function is given by Plowright (Plowright and Plowright, 1988; Bonabeau et al., 1999):

$$T_\theta(s) = 1 - e^{-s/\theta} \tag{2}$$

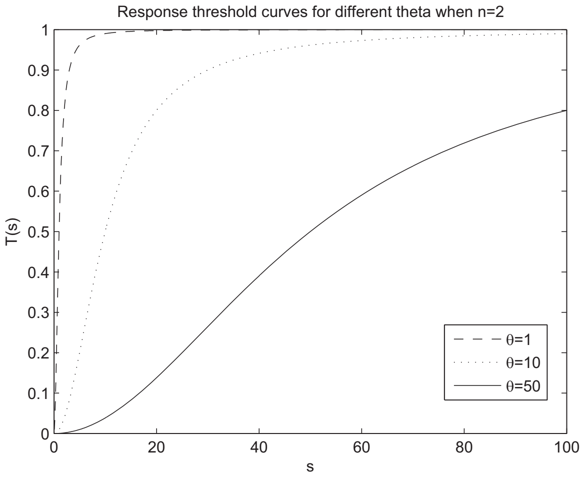

Fig. 1. Response threshold curves based on Eq. (1).