Decentralised Control of Adaptive Sampling and Routing in Wireless Visual Sensor Networks

(Extended Abstract)

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ABSTRACT

The efficient management of the limited energy resources of a wireless visual sensor network is central to its successful operation. Within this context, this paper focuses on the inter-dependent adaptive sampling and routing actions of each node in order to maximise the information value of the data collected. Thus, we develop two optimal decentralised algorithms to solve this distributed constraint optimization problem. The first assumes fixed routing and works in tree-structured networks. The second works in networks with any topologies by using a flexible routing approach. The two algorithms represent a trade-off in optimality, communication cost, and processing time. In an empirical evaluation on loopy sensor networks, we show that the flexible routing algorithm is able to deliver approximately twice the quantity of information compared to the fixed routing algorithm, where an arbitrary choice of route is made. However, this gain comes at a considerable communication and computational cost (increasing both by a factor of 100 times).

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence

General Terms

Algorithms, performance

Keywords

Decentralised mechanism, information metric, inter-related adaptive sampling and routing algorithm

1. INTRODUCTION

The rapidly increasing computational power of the nodes deployed within wireless sensor networks has allowed them to perform ever more sophisticated tasks, and recently, *wireless visual sensor networks* (WVSN) have received increasing attention within the research community [1, 3]. The large amounts of visual information that they collect and the high energy cost of wirelessly communicating this information through the network, mean that efficient energy management is a key challenge in these networks. Recent work has explored decentralised coordination algorithms that enable the nodes to autonomously adapt and adjust their sampling and routing behaviours. This coordination is computationally expensive since the two decisions are inter-dependent. This is because each node's energy consumption must be optimally allocated between *sampling* and *transmitting* its own data, *receiving* and *forwarding* the data of other nodes, and *routing* any data. Against this background, we develop an optimal decentralised adaptive sampling and routing algorithm that varies each node's sampling, transmitting, and forwarding rates to ensure all nodes focus their limited resources on maximising the information content of the data collected at the base station. This algorithm assumes that the route by which data is forwarded is *fixed*. We then extend this approach to deal with *flexible* routing, in which each node not only makes optimal decisions regarding the integration of actions, but also determines the optimal route by which this data should be forwarded. We empirically evaluate them and show that they represent a trade-off in optimality, communication cost, and processing time.

2. PROBLEM DESCRIPTION

Now, let n be the number of nodes within a WVSN system and the set of all nodes be $I = \{1, \dots, n\}$. Each node $i \in I$ can sample at s_i different rates over a period of time. Its set of possible sampling (or frame) rates is denoted by $C_i = \{c_i^1, \dots, c_i^{s_i}\}$. Each node has private information regarding the information content of the samples it acquires, and this is represented by an array of 2-tuples, $\mathfrak{F}_i = \left[(0,0), \left(c_i^1, v_i^{c_i^1}\right), \dots, \left(c_i^{s_i}, v_i^{c_i^{s_i}}\right)\right]$, where the first value of each tuple is the number of samples that the node may take and $v_i^{c_i^j}$ is the corresponding information content. We define $v_i^{c_i^j} = \alpha_i c_i^j$, where α_i is a weighting factor that models the typical situation that the sensors within the network are heterogeneous. Our algorithms are, however, not restricted to any particular types of information valuation function. We further assume that each node has an energy budget, B_i, (also a private value) and here, we consider three kinds of energy consumption for each node; namely to (i) acquire, e_i^{s}, (ii) transmit, e_i^{Tx}, and (iii) receive, e_i^{Rx}, a single sample. Now, since the node has to transmit its own data, the total energy required for this *sensing* activity is thus $E_i^{\mathrm{S}} = e_i^{\mathrm{s}} + e_i^{\mathrm{Tx}}$ per sample. Similarly, the node could spend a portion of its energy to help other nodes to *forward* their samples; this requires a total energy of $E_i^{\mathrm{F}} = e_i^{\mathrm{Rx}} + e_i^{\mathrm{Tx}}$ per sample. We describe the route through which the samples, c_i^j, will be transmitted to the base station by the vector $R\left(c_i^j\right) = (r_i^1, \dots, r_i^b)$, where $r_i^l \in I$ and r_i^l will forward the data to r_i^{l+1}.

Now, we wish to maximise the value of the collected data that

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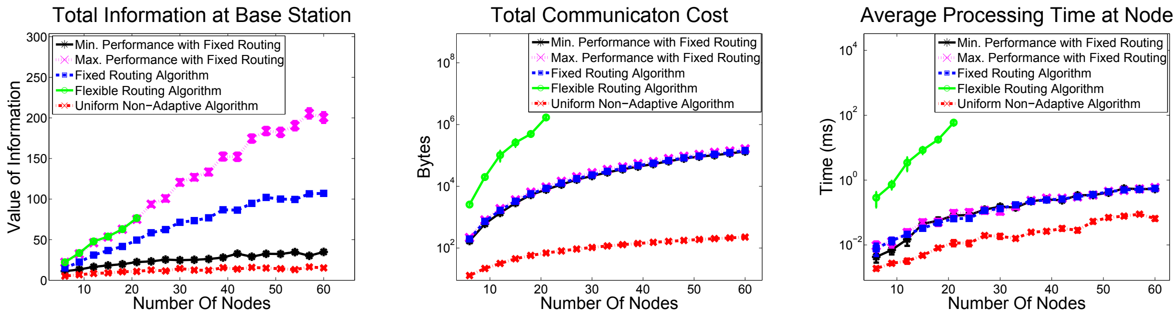

(a) (b) (c)

Figure 1: Simulation results showing the performance of the algorithms with flexible, fixed (with maximum and minimum performance), and uniform non-adaptive routing against (a) total information collected at the base station, (b) total communication cost for coordination, and (c) average computation time at each node.

arrives at the base station. That is, we wish to solve:

$$\arg\max_{x_i^{R(c_i^j)}} \sum_{i=1}^{n} \sum_{c_i^j \in C_i} x_i^{R(c_i^j)} v_i^{c_i^j} \tag{1}$$

In this expression, $x_i^{R(c_i^j)}$ is a decision variable where "1" represents a state where node i carries out its c_i^j sampling action and the samples follow the $R\left(c_i^j\right)$ route. "0" represents the state where the node does not carry out this sampling action. This objective function is maximised subject to the energy budget constraint:

$$B_i \geq c_i^j E_i^{\mathrm{S}} + f_i E_i^{\mathrm{F}} \tag{2}$$

where $i \in I$ and f_i represents the total incoming data (or forwarded samples from its set of neighbourhood nodes, D_i) and is given by:

$$f_i = \sum_{d \in D_i} c_d^j + f_d \tag{3}$$

We must also constrain the node to choose one and only one sampling rate for all different possible routes in the network, such that:

$$\sum_{c_i^j \in C_i} x_i^{R(c_i^j)} = 1 \tag{4}$$

The problem, as formulated above, is similar to *multiple-choice knapsack* problems (i.e. NP-complete resource allocation or distributed constraint optimization problems), that exhibit the *optimal substructure* property. Given this insight, we propose algorithms based on the sort of computationally efficient dynamic programming technique that are often used on such knapsack problems for solving multi-agent distributed coordination problems [2].

3. THE ALGORITHMS

We now focus on the algorithms in which nodes are required to make optimal use of their resources to cooperatively sense and forward data to the base station. This is achieved by exchanging coordination messages between connected nodes and maximising the objective function in (1), subject to constraints in (2) and (4).

In the case of fixed routing, each node can only forward its data to exactly one other node. This may be because the underlying network of the WVSN is tree-structured, or because it actually exhibits loops but an arbitrary choice of route has been made. Note that in such networks, there is only one unique route between each node and the base station. On the other hand, in the case of flexible routing, we assume that the data of different nodes could be sent through different shortest path routes to the centre, and we optimise both the route and the sampling, transmitting, and forwarding actions of each node. Both algorithms are efficient as they satisfy the data flow conservation of the network where no energy is wasted by transmitting data that later will not be propagated.

4. EMPIRICAL EVALUATION

We evaluate the performance and effectiveness of these algorithms by simulation. Figure 1 shows that the flexible routing algorithm is able to deliver significantly more information, but incurs considerable additional computation and communication costs in doing so. The choice of algorithm thus largely depends on the actual application domain. If the network is small, and the size of the actual data messages is large, then the flexible routing algorithm is most appropriate. However, this algorithm scales poorly as the size or connectivity of the network increases (due to the exponential growth in the number of possible combinations of routing options). To address this, the fixed routing algorithm may be run on the original loopy network by having each node make an arbitrary choice of route. This solution will scale well using minimal communication and computational resources.

5. CONCLUSIONS

In this paper, we have considered the problem of inter-dependent adaptive sampling and routing within a WVSN in order to manage the limited energy resources of nodes in an effective and efficient way. We have developed two optimal decentralised algorithms: one which assumes fixed routing and calculates the optimal actions that each node should perform, and one which assumes flexible routing, which also makes an optimal decision regarding the route by which the collected data should be forwarded to the base station.

6. REFERENCES

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