Forest fire localization using distributed algorithms in wireless sensor networks

A.Khadivi, L.Georgopoulos, and M.Hasler
School of Computer and Communication Sciences,
Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland

Abstract The fire localization using a distributed consensus finding algorithm in a wireless sensor network is described. The fire is circumscribed by a circle. The information is available at all sensor nodes that are alive, which makes it robust against failures and losses. Minimizing energy consumption is crucial for sensor nodes that have to function autonomously as long as possible. Therefore, the speed of convergence of the consensus finding algorithm has to be optimized. We argue that optimizing, as is customary, the asymptotic speed of convergence is not the best method when a consensus value of low precision is sufficient.

1. INTRODUCTION

Wireless sensor networks are a new technology that starts being deployed for various applications, in particular for environmental monitoring. In this paper we are in particular addressing the monitoring of forest fires. Wireless sensor networks potentially can alert the fire brigades very shortly after the outbreak of a forest fire and give continuously information about its localization, even if the outbreak is in a very remote area. The main challenges are:

- The sensor and the wireless communication module at a node of the network should consume as little energy as possible. Therefore, as long as no fire has been detected, the communication module should be in a “sleep” mode. Nevertheless, it should be able to wake up in a very short time, either when its sensor detects a fire outbreak in its vicinity, or when it receives an order to wake up from a neighboring node.
- Again for energy conservation purposes, a communication module is restricted to communicate only with its neighbors. Thus, direct communication with a central base station is for most nodes in the network impossible. Therefore, a multi-hop protocol has to be adapted and/or information has to be elaborated locally.
- The fire will destroy part of the network as it progresses.

We suppose that at each network node, a temperature sensor is located that periodically takes measurements and makes them available for the communication module. The nodes are location aware, which can be achieved at network deployment time. Through iterated information exchange with its neighbors and processing, every node has all the information about the fire available. This information can thus be extracted by fixed or mobile means from any node of the network that is alive and communicated to the fire brigades. This makes the network robust against local failures.

The distributed computing approach in sensor networks has recently been described in the literature [1,2]. The contribution of this paper is twofold:

- To enhance the speed of convergence of the algorithm in its initial phase.
- To show how the fire can be localized with distributed algorithms.

Here, the ideas are spelled out, but the details will be given elsewhere [3,4].

2. SPEEDING UP CONSENSUS FINDING

As will be explained later, the basic mathematical operation to be performed is the computation of a mean value (also called consensus value) of a scalar quantity (e.g. temperature) over the whole or over part of the network. This cannot be done in one step since the various nodes can communicate only with their neighbors. However, a simple iterative algorithm allows reaching consensus, in theory only asymptotically in time, but in practice after a certain number of iterations. At each node and at each time step, taking the mean value of the current estimation of the quantity among the node and its neighbors is the simplest approach. Replacing the mean by a weighted mean [1] allows speeding up the convergence, which is important for energy conservation.

We suppose the network is obtained by randomly placing n sensor nodes in a finite area (the forest) according to a uniform probability density (they might be dropped by an airplane). Sensor nodes within wireless communication range are linked by an edge. We suppose that the resulting graph is connected. Let $x_i(t), t = 0,1,2,\cdots$ be the state of node i at time t. It is initialized at $x_i(0)$, typically the unprocessed sensor measurement. For the linear consensus finding algorithm the update equation is

$$x_i(t+1) \quad = \quad \sum_{j=1}^{n} w_{ij} x_j(t) \tag{1}$$

or in vector form

$$\boldsymbol{x}(t+1) \quad = \quad \boldsymbol{W}\,\boldsymbol{x}(t) \tag{2}$$

The interaction weights w_{ij} are only different from zero if nodes i and j are within wireless communication range, i.e. joined by an edge of the graph. We suppose that the matrix $\boldsymbol{W}$ satisfies in addition the following conditions:

$$w_{ij} \geq 0 \text{ for } i \neq j, \quad \sum_{j=1}^{n} w_{ij} = 1 \text{ for all } i, \quad \boldsymbol{W} = \boldsymbol{W}^T, \quad \boldsymbol{W1} = \boldsymbol{1}, \quad \rho\left(\boldsymbol{W} - \frac{1}{n}\boldsymbol{11}^T\right) < 1 \tag{3}$$

where "T" denotes the transpose and ρ the spectral radius of a matrix and $\boldsymbol{1}$ is the column vector composed of all 1's. These conditions guarantee that consensus is always reached:

$$\boldsymbol{x}(t) \xrightarrow[t\to\infty]{} \left[\frac{1}{n}\sum_{i=1}^{n} x_i(0)\right] \cdot \boldsymbol{1} \tag{4}$$

Furthermore, the speed of convergence to consensus can be deduced from [2]

$$\boldsymbol{x}(t) \quad - \quad \left[\frac{1}{n}\sum_{i=1}^{n} x_i(0)\right]\cdot\boldsymbol{1} \qquad = \qquad \left(\boldsymbol{W} - \frac{1}{n}\boldsymbol{1}\boldsymbol{1}^T\right)^t \boldsymbol{x}(0) \tag{5}$$

The question is now how to choose the nonzero interaction coefficients such that convergence is as fast as possible. For this purpose, it is useful to remark that $\boldsymbol{W} = \boldsymbol{I} - \boldsymbol{L}$ where $\boldsymbol{I}$ is the identity matrix and $\boldsymbol{L}$ is the weighted graph Laplacian. Since the eigenvalues of $\boldsymbol{L}$ are nonnegative, the eigenvalues of $\boldsymbol{W}$ satisfy $1 = \lambda_1 > \lambda_2 \geq \cdots \geq \lambda_n$. The eigenvector for eigenvalue 1 is $\boldsymbol{1}$. Therefore, the eigenvalues of $\boldsymbol{W} - \frac{1}{n}\boldsymbol{1}\boldsymbol{1}^T$ are 0 and $1 > \lambda_2 \geq \cdots \geq \lambda_n > -1$. The first and the last inequalities are strict, because of the condition on the spectral radius in (3). Clearly, due to (5) the asymptotic exponential convergence rate is given by $\min\left\{\left|\ln\left(1-\lambda_2\right)\right|, \left|\ln\left(\lambda_n+1\right)\right|\right\}$. In [2] it is shown that the matrix $\boldsymbol{W}$ that maximizes the asymptotic convergence rate can be found by convex optimization.

In Figure 1, the error

$$Err(t) \quad = \quad \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left[x_k(t) \; - \; \frac{1}{n}\sum_{i=1}^{n} x_i(0)\right]^2} \tag{6}$$

as a function of the iteration t is represented, averaged over 100 instances of Gaussian distributed random initial vectors $\boldsymbol{x}(0)$. The upper curve corresponds to weights obtained by convex optimization and the lower curve by the Metropolis-Hastings weights

$$w_{ij} \quad = \quad 1/\max\left\{d_i, d_j\right\} \;\text{ for }\; i \neq j, \qquad w_{ii} \quad = \quad 1 \; - \; \sum_{i \neq j} w_{ij} \tag{7}$$

where d_i is the number of edges connected to node i. The asymptotic rate of convergence is higher for the optimized weights, as it should be. However, if a precision of only about 0.1 is desired, the algorithm with the Metropolis-Hastings weights needs only about half as many iterations to reach this goal. In [3] it is shown that a nonlinear algorithm is able to combine both fast transient and optimal asymptotic convergence.

3. FIRE LOCALIZATION

Various distributed algorithms of the cellular automata type can be designed for fire alert. An example where all nodes of the network after a short time are alerted is described in [4]. We shall concentrate on the subsequent processing action of the sensor network, namely to localize the fire within a circle, because it is entirely based on consensus finding as described above.

At regular intervals, a consensus algorithm is run that approximates the perimeter of the fire by a circle. It is initialized by determining all sensor nodes that show an intermediate temperature (e.g. between 30°C and 150°C). The consensus algorithm is only run among these nodes. Denote their indices by $i_1, \cdots, i_m$, and suppose their geographical positions are $\left(x_{i_1}, y_{i_1}\right), \cdots, \left(x_{i_m}, y_{i_m}\right)$. Then, we determine a circle of radius r and center (u,v) such that the mean square error of the radius

$$D(u,v,r) = \frac{1}{m}\sum_{k=1}^{m}\left[\sqrt{\left(x_{i_k}-u\right)^2+\left(y_{i_k}-v\right)^2}-r\right]^2 \tag{8}$$

is minimal. This is a nonlinear least squares problem that can be solved by a sequence of linear least squares problems. It can be shown [4] that the linear least squares problem is solved, using some simplifying assumption, by computing the following three mean values

$$\begin{aligned}
&\frac{2}{m}\sum_{k=1}^{m}\frac{x_{i_k}-u}{\sqrt{(x_{i_k}-u)^2+(y_{i_k}-v)^2}}\cdot\left(\sqrt{\left(x_{i_k}-u\right)^2+\left(y_{i_k}-v\right)^2}-r\right)\\
&\frac{2}{m}\sum_{k=1}^{m}\frac{y_{i_k}-v}{\sqrt{(x_{i_k}-u)^2+(y_{i_k}-v)^2}}\cdot\left(\sqrt{\left(x_{i_k}-u\right)^2+\left(y_{i_k}-v\right)^2}-r\right)\\
&\frac{2}{m}\sum_{k=1}^{m}\left(\sqrt{\left(x_{i_k}-u\right)^2+\left(y_{i_k}-v\right)^2}-r\right)
\end{aligned} \tag{9}$$

which is achieved by a consensus algorithm. The result, i.d. the center (u,v) and the radius r of the circle is communicated to all alive sensor nodes by multi-hop communication. The sensor nodes whose temperature is above a certain threshold (e.g. 200°C) are supposed to be dead. This neither disturbs the consensus algorithm among the nodes at the border of the fire nor the spreading of the information to all other alive sensor nodes.

In Figure 2, the efficiency of the fire localization algorithm is shown. The evolution of the fire is simulated by the FARSITE fire simulation software [5]. The nodes in the border of the fire are marked by dark read, the dead nodes and the computed circle is green. Clearly, the circle is a good approximation of the border of the fire.

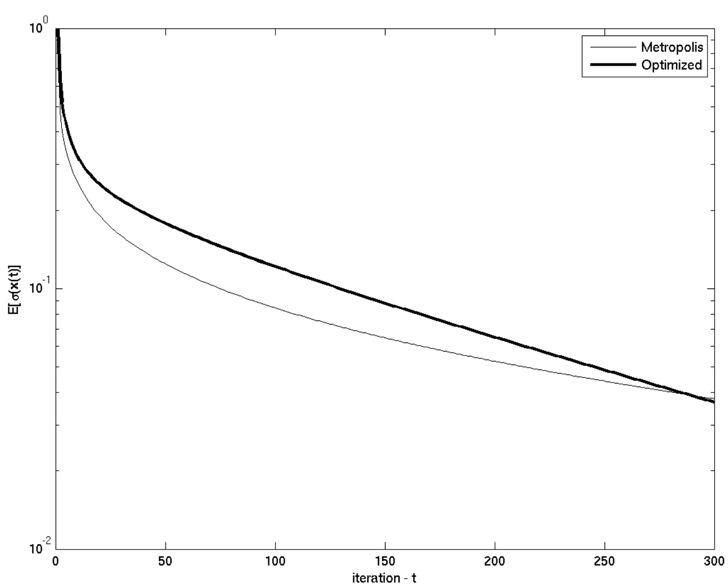

Fig. 1. Evolution of the *Err*(t) defined in (6) as a function of time. Bold: Connection weights obtained by convex optimization. Clearly the error has a faster asymptotic convergence rate Normal: Metropolis Hastings connection weights. The error decreases faster in the transient phase.

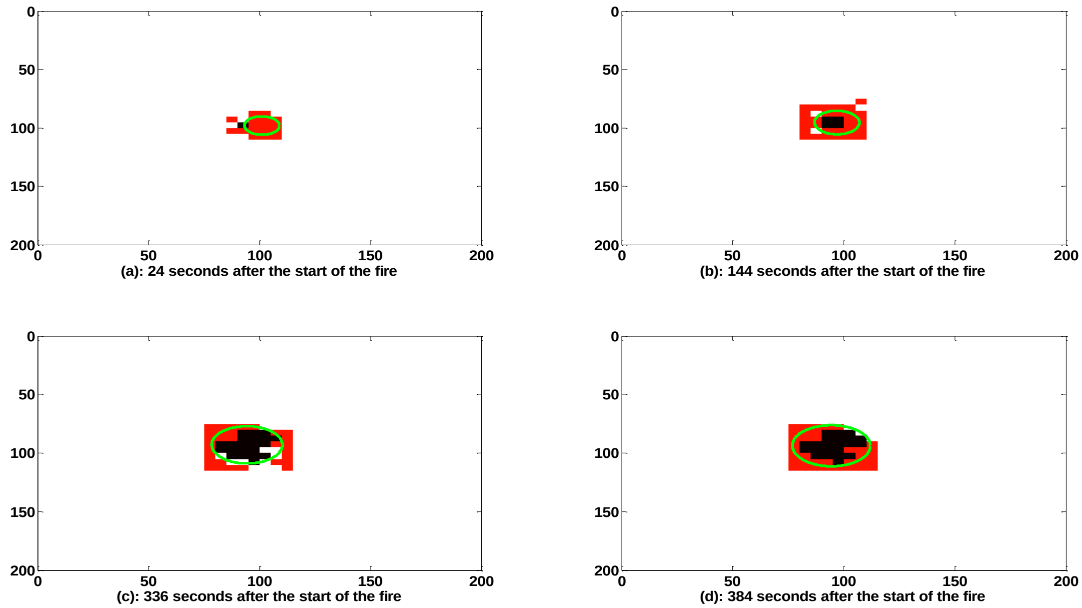

Fig.2. Sensor network deployed in a 200m x 200m area. Each 5m x 5m cell contains one sensor, placed in a random location. In the figure, the state of a sensor node is indicated by a color filling out the whole cell. Evolution of the border (red) of the fire (temperature between 30^{o}C and 150^{o}C) in time, and the circle approximating it (green), computed by a consensus algorithm among the nodes in the border. The black sensor nodes are dead. The other sensors that are alive without being in the border of the fire are colored in white.

4. CONCLUSIONS

We have shown how to use a consensus algorithm for fire localization by circumscribing it by a circle. The center and the radius of the circle are determined by repeated application of a distributed consensus algorithm. The information is made available at all sensor nodes that are still alive, which makes it robust against failures and losses. For energy conservation purposes, it is important to speed up the consensus finding algorithm. It is well known that this can be done by suitably weighting the edges of the network graph. However, we point out that the usual solution that optimizes the asymptotic convergence rate may not be optimal when a low precision of the result is sufficient.

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